GEOCHEMISTRY, PETROLOGY AND MINERALISATION AT RIRIWAI, GINDI AKWATI AND DUTSEN WAI IN THE NIGERIAN YOUNGER GRANITE PROVINCE.

BY

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THESIS SUBMITTED TO AHMADU BELLO UNIVERSITY, ZARIA, FOR THE AWARD OF THE DEGREE OF MASTER OF SCIENCE IN GEOLOGY.

AHMADU BELLO UNIVERSITY,
ZARIA

1976.

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A C K N O W L E D G E M E N T S

I would like to express my gratitude to Dr. D.C. Turner for arranging this Research and his criticism of the manuscript and further advice; Dr. P. Bowden (University of St. Andrews) for his assistance in field work and for arranging for me to come to the University of St. Andrews without which this project would not have been accomplished.

Thanks are also due to the Gold and Base and the X-Lands Mining Companies for supplying rock cores for part of this Research. I also appreciate immensely the help of Mrs. J. Kinnaird (a M.Sc. research student of University of St. Andrews) who through discussion and thin section study made valuable suggestions to me. I am also grateful to Mr. John Bennett for his assistance in the field as well as his useful advice on references, during discussions and criticisms. My thanks go to Dr. J. Whitley of the Scottish Universities Research and Reactor Centre; Dr. F. Hubbard of the University of Dundee and all the staff, particularly the technicians of the Department of Geology, University of St. Andrews for their cooperation during the period of my work in St. Andrews.

A B S T R A C T

The Nigerian Younger Granite Province is composed of anorogenic Mesozoic ring complexes which were subjected to two distinct processes of differentiation, resulting in two series; the hornblende - fayalite - granite to hornblende - biotite - granite to biotite-granite and the hornblende-fayalite-granite to arfvedsonite - fayalite - granite to riebeckitic - arfvedsonite - granite. Of the two end members; biotite granite is peraluminous while the riebeckitic - arfvedsonite - granite is peralkaline Both rocks can be closely associated and have been Mineralised.

The geochemistry and petrology of three selected mineralised areas of this Younger Granite Province have been studied. Detailed maps of the mineralised zones have been produced. Samples were selected from the surface as well as from cores at depth and both altered and unaltered samples have been studied mineralogically and by chemical analyses. The results of the chemical analyses and petrological studies have been used to suggest the composition of the mineralising fluids, the alteration processes and the ore minerals formed.

At Ririwai, two phases of mineralisation have been found; a pre-joint autometamorphic mineralisation in which K-feldspars replaced earlier perthites, while new albite developed. Silicification and re-crystallisation changed the original rock texture and introduced dispersed mineralisation with thorite, columbite, xenotime and hafnium-uranium rich zircon as well as enrichment in some trace elements. The second phase of mineralisation was a post-joint replacement greisen-mineralisation which took place in the roof zones of the cooling consolidated biotite granite.. It involved a metasomatic introduction of cassitorito and sul-phide ores into the crystalline biotite granite along cooling joints, fissures and fractures. The sequence of replacement has been found to be haematisation and kaolinisation - chloritisation and sericitisation -

greisenisation - silicification.

At Gindi Akwati, only post-joint replacement mineralisation occurred in the Older Granite with introduction of cassiterite, sulphide ores and some trace elements which were also enriched in the associated dolerite, dykes. The alteration started by shearing and mylonitisation - argillisation and haematisation -chloritisation and museovitisation - greisenisation - silicification and feldspathisation - feldspathisation.

At Dutson Wai, the roof zones of the biotite granite were affected by post joint mineralisation, and weathering of the roof zones of the granite concentrated cassiterite in the alluvials. In the per-alkaline granite, there was recrystallisation with introduction of albite, microcline and the accessory minerals cryolite, pyrochlore, amblygonite and astrophyllite.

From the ore minerals formed, and the chemical and mineralogical composition of the altered wall rocks and the unaltered rocks, it is shown that in the peralkaline granite, at the time of crystallisation, residual fluids became increasingly enriched in volatiles as temperature dropped and crystallisation continued. The fluids continued to change continuously from an agpaitic magma to a sodium - silicate rich hydrothermal solution without supercritical phenomena, and the magmatic fluids progressed to hydrothermal fluids without an aqueous phase seperating off. At late stages, and near surface conditions, the confining pressure decreased to below the hydrostatic pressure, causing an immiscible liquid consisting predominantly of salts and volatiles to separate. This led to riebeckitisation of arfvedsonite, introduction of albite, quartz and microcline, mineralisation with pyrochlore, cryolite and astrophyllite and enrichment in some trace elements.

In the biotite granites, as fractional crystallisation continued, the concentration of volatiles increased in the residium until saturation

when an aqueous phase separated. The cooler crystalline portions of the granites in the roof zones of the intrusions were invaded by the then immiscible phases from the still crystallising granites at slightly deeper levels, causing albitisation, dispersed mineralisation with thorite, columbite, xenotime as well as enrichment in some trace elements. The late hydrothermal fluids introduced cassiterite with sulphide minerals into crystalline host rocks along cooling joints, fissures, fractures and even faults and the regional foliation of the Basement rocks were utilised. This form of mineralisation was accompanied by wall-rock alteration, while the cassiterite was transported in the ore fluids in the form of alkali-thio-stannate or/and in the form of hydroxofluor-stannate complex of tin of the $[SnF_x (OH)_{6-x}]$ type.

CHAPTER 1

INTRODUCTION

Previous Work

The first survey of the Geology of the Nigerian tinfields was undertaken by the Geological Survey of Nigeria in 1919 when it was formed (MacLeod *et al*; 1971), and the Survey unveiled the importance of the Younger Granites as a source of the abundant tin mineralisation, and also provided maps which delineated the boundaries of the Younger Granites. A resurvey of the central area of the tinfields including the Jos Plateau was carried out between 1945 and 1948 and has been described in Bulletin of the Geological Survey of Nigeria No. 19 (Mackay *et al*; 1949). The report gave more precise boundaries of the Younger Granite complexes, recognised some of the major ring complexes, described the distribution of the alluvial tin and columbite as well as the rocks of the Basement Complex. Another study on the Younger Granites was in 1950 when the occurrence of radioactive minerals in the rocks was investigated (Mackay and Beer; 1952). A further resurvey (MacLeod; 1956) was carried out and the distribution of columbite was described. Following this study, the survey was extended from the Jos Plateau to the whole of the Younger Granite Province, and the crystalline Basement Complex (MacLeod, 1951-1957; Black, 1953-57; Turner, 1957-59); with a full description of the whole province published as a Memoir of the Geological Society of London (Jacobson *et al*; 1958).

From then to the present time, many workers have published various papers on the Nigerian Younger Granites

concerning their mineralogy, geochemistry, age, geophysical properties and mineralisation. Some of these are Bond (1956) who gave a preliminary account of the Pleistocene geology of the plateau tinfields; Borley (1963) who studied the amphiboles and geochemistry of the mafic minerals in some of the Younger Granites; Bowden (1961) who studied the geochemistry of some of the igneous rocks, and has since then written several papers on some geochemical, isotopical, mineralization and age trends in the various complexes of the province; Butler et al. (1962) who studied K/Rb ratios in the evolution of the Younger Granites; Smith et al (1962) who studied zirconium, niobium and certain other elements in some of the igneous rocks; Thompson et al (1963) who studied Caesium in some alkali granites of the province. Other workers include Carter et al (1963) who studied the geology of parts of Adamawa, Bauchi and Bornu provinces of Nigeria; Jones (1960) who carried out mineral dressing tests on the extraction of columbite and other heavy minerals from the Odegi Younger Granite; Knorring et al (1959) who studied the occurrence of genthelvite in the Younger Granites. Several other papers have appeared in different literature concerning different aspects of these rocks.

Outline of Regional Geology.

The Nigerian Basement Complex covers about $\frac{2}{3}$ of the non-sedimentary areas and is composed of granulitic gneisses, mainly psammitic and semi-pelitic gneisses; granite gneisses and migmatic granite-gneisses believed to have been derived from Older gneisses by granitisation in situ; and medium-fine grained muscovite-biotite granites

(Wright, 1971; Oyawoye, 1965). The Nigerian Basement rocks have been assigned to late Cambrian to Ordovician orogeny and correlated with similar rocks from Dahomey (Bonhomme; 1962). Age determinations (Jacobson et al; 1963) from biotites using K/Ar dating gave the Basement rocks an age of more than 500 my.

The Younger Granites within which three areas of this study have been selected lie in the north central part of Nigeria, extending from the Benue valley to the south of Kano State for a distance of about 420 km (Fig. 1.1). Similar granites occur to the north-east in the Matsena area of Borno State (Turner; 1974); around Zinder and Air plateau in Niger Republic (Bowden and Turner; 1974) and in the Sahara, Cameroun and Sudan (MacLeod and Turner; 1971). The Younger Granite Complexes of Nigeria occupy a total area of about 10,440 km^2, individual masses ranging from less than 2 km^2 to 1,800 km^2, with a circular or elliptical outline and a maximum diameter of about 24 km (MacLeod and Turner, 1971; Jacobson et al, 1958). The rocks are discordant high level intrusions, cutting across the basement rocks. The Younger Granites were preceded by acid volcanism and emplaced by ring faulting and block subsidence (Turner; 1963). The rocks are mostly acidic in composition and are mainly granites and rhyolites with most of the syenites containing quartz, while other intermediate and basic rocks of gabbroic and doleritic compositions are subordinate to the acidic rocks in aerial extent.

The major granite types are hornblende-pyroxene-fayalite-granites, biotite-granites, and riebeckitic-arfvedsonite-granites. The granites have been classified as soda-potash granites usually having a slight excess of soda

Figure 1.1 is a sketch map of the Nigerian Younger Granite Province, and the three areas of study are shown.

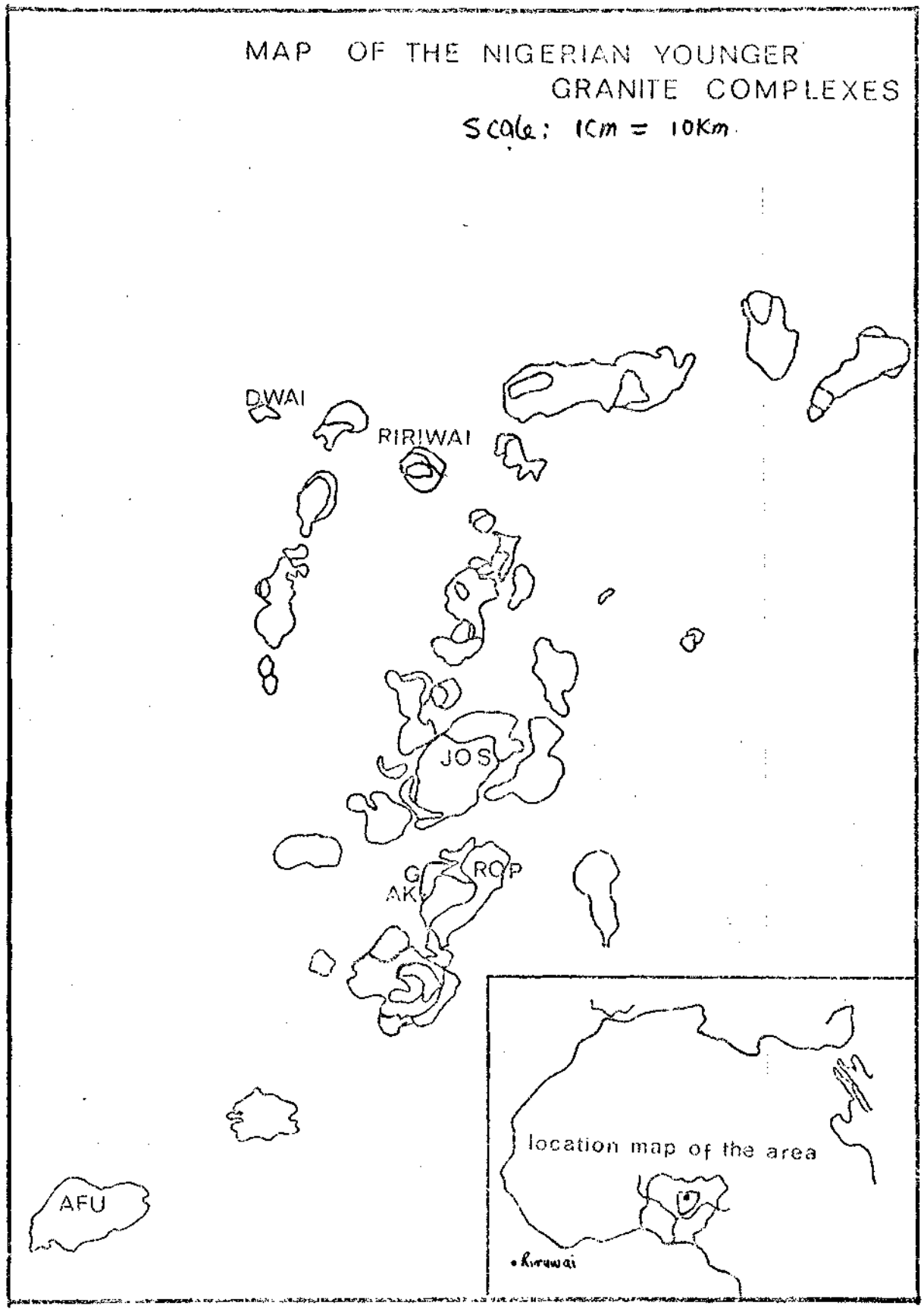
D. Wai = Dutsen Wai.

G. Ak. = Gindi Akwati

Ririwari.

Scale: 1cm = 10km.

FIG. 1.1


MAP OF THE NIGERIAN YOUNGER GRANITE COMPLEXES
Scale: 1Cm = 10Km
DWAI
RIRIWAI
JOS
AFU
location map of the area
Kirawai

over potash, except in a few cases when the albite-riebeckitic-arfvedsonite granites may be highly enriched in soda due to late stage albitisation.

Age determinations have shown that the Nigerian Younger Granites are of Jurassic age (Jacobson et al; 1963). Bowden et al (1976) using Rb-Sr. whole rock isochrons, found the complexes to decrease in age from about 190 ± 10 my in the north to 144 ± 2 my in the south. They found that the range of dates was indications that the individual granitoid ring complexes were not emplaced into the upper crust at the same time, but evolved during the upper Triassic and Jurassic. These Younger Granites and their environments contain the major tin-columbite-sulphides mineralisation in Nigeria.

Geography of the Area.

The Younger Granites consist of isolated uplands, some rising to about 1220 m from the surrounding plains. The area varies in topography from level flat plains, and plateaus lacking exposed rocks, to rugged, deeply dissected massifs, arising from the more resistant rocks. The emplacement of the Younger Granites was followed by a period of erosion and deposition of alluvium by rivers and streams. Then during the early Tertiary, the alluvium deposits were covered by lava flows of the Older Basalts. The basalts have been largely decomposed to clays and these are in turn capped by laterites, forming isolated, tall, flat topped hills in the Jos Plateau Area. These fluvio-volcanic hills may be up to 40 m thick and one of such hills occurs at about 1,535 m above sea level at the Vom-Ganawuri Granite (Dixey, 1945). Later deposits of alluvium and a further volcanic phase gave rise to cones and lavae flows of the

Newer Basalts. The Younger Granite province thus has provided isolated hills in its northern part where thick woods and bushes are abundant. In the south, the rocks usually form continuous mountain ranges and plateaus. The area is drained mainly by the rivers Kaduna, Gongola and the Chad system, and the general and local drainage systems are usually radial.

The climate of the area is marked by three distinct seasons:-

a, Late Nov-Feb.: Harmattan (Winter), forms part of the dry season with the Sahara Desert winds blowing north-easterly with plenty of dust. Temperatures at this time hardly exceed $80^{o}F$.

b, March-May: Dry Season, usually very hot with little rain in some places. The wind blows from northeast to south-west and temperatures may be as high as $105^{o}F$.

c, May-Sept: Wet or Rainy Season (Summer), winds blow in a south-westerly direction with occasional sunshine and temperatures may reach $90^{o}F$ in some places. Sept.-late Nov. may correspond to Autumn and is not well marked, usually characterised by winds from south-west to north east. Rains may sometimes be heavy in October finally fading in early November.

The vegetation corresponds to the Sudan-Savannah type with grass as tall as 1 m in the rainy season and some well scattered trees in some areas. Further north the trees give way to thorny shrubs. The mean annual rainfall is about 150 cm in the south, decreasing to less than 100 cm in the northern part of the province. The mean Relative Humidity at 0600 hours and 1200 hours is 50 percent and 58 percent respectively (Schroeter, 1974).

Aims and Scope of the project.

Although much work has been done on the Nigerian Younger Granites and their associated mineralisation, not all the individual areas have been mapped in detail. Similarly, there has been no thorough investigation of the mineralisation in such areas. Besides, even in the areas where mining companies operate, information is available mainly on the ores in which the mining companies are interested only. As such, the relationships between the different mineralised areas and the processes involved in the mineralisation of the areas have not been well established. In general, information is lacking on the particular ore minerals that occur in a particular area as well as the actual environment in which they occur.

The aims of this project were:-

(1) To produce a detailed map of the Ririwai lode, the associated veins and the accompanying zones of the altered wall-rock.

(2) To study the chemical changes accompanying the mineralisation, the processes involved in the wall-rock alteration, the extent of the lode at depth and the changes in wall-rock alteration with depth.

(3) To produce a detailed, accurate large scale map of the Gindi Akwati primary mineralised zone, study the processes and chemical changes accompanying the mineralisation as well as establishing the order of emplacement and shearing of the different rock types in the area.

(4) To ascertain the extent of cassiterite mineralisation in the Gindi Akwati zone for a possibility of developing a mine.

(5) To produce an accurate and detailed map of the Dutsen Wai granite complex as well as finding the source of the alluvial cassiterite in the area.

(6) To identify the ore minerals present in the three areas, and to add more information to the existing one on the Younger Granites and their associated mineralisation.

In order to produce a map of the Ririwai lode, overlays were taken directly from air photographs of the lode on the scale of 1:5000. The rest of the information on the map was plotted from data obtained with a compass and tape measurements. For analytical work, rock samples were obtained from cores (Ririwai, L 13) to a depth of 450 m, while greisen samples were obtained from adits.

At Gindi Akwati, the boundaries of rocks were first surveyed in with the assistance of the Ex-Lands mining company surveying staff. The geology was put on the survey map using a plane table, and where necessary a measuring tape was used. Two cores were drilled to a depth of about 50 m each and a core diagram was drawn. Samples were further selected from the cores for analytical work.

The Dutsen Wai map was made by examining the rocks from place to place with the aid of air photographs and a topographic base map on a scale of 1:25,000 (sheet 125 NW). Fresh samples for analytical work were obtained from rock boulders using a sledge hammer.

Analytical methods.

The analysed samples were first crushed and ground to about 200 mesh in a TEMA mill. The powders obtained were bottled and different methods used to analyse for different elements.

(1) SiO_2, Al_2O_3, TiO_2, total Fe, MnO, CaO, K_2O and P_2O_5.

These oxides were analysed for by X-ray fluorescence spectroscopy. 0.3750g of the powdered samples were mixed with about 2g of borax flux. The mixture was fused at about 1,200°C and pressed into glass beads using a graphite disc, a brass ring and an aluminium plunger kept on a hot plate at about 200°C. The beads were allowed to cool and later compared with beads of known element contents on the XRF. Calibration curves of beads with known element percentages against ratios of counts obtained on XRF from standards and counts from prepared beads of known elemental content. Equations were derived from these curves and used to calculate the elemental contents of the unknown samples. Two of such curves and equations for Total Fe and Na are presented here (Fig. 1.2). The fluorescent intensity due to the elements concerned was measured for a fixed time, usually 10 sec. For each sample 3 readings of the peak intensity and background intensity were obtained and their mean found. The background intensity was subtracted from the peak intensity and the nett intensity was divided by the standards nett intensity and the ratio substituted in the calibration equations to find the percentage of each element. The accuracy was estimated to be about $\pm$ 0.5 percent (Norrish and Chappell, 1967).

(2) MgO, Na_2O F and Cl.

Due to the matrix effect these elements were analysed directly from the powders in form of pressed pellets. About 6g of samples were ground in a mortar with about 6 drops of a liquid adherent and the resultant ground

Fig1-2 Calibration curve for Fe

$Y = 9.93x - 0.24$

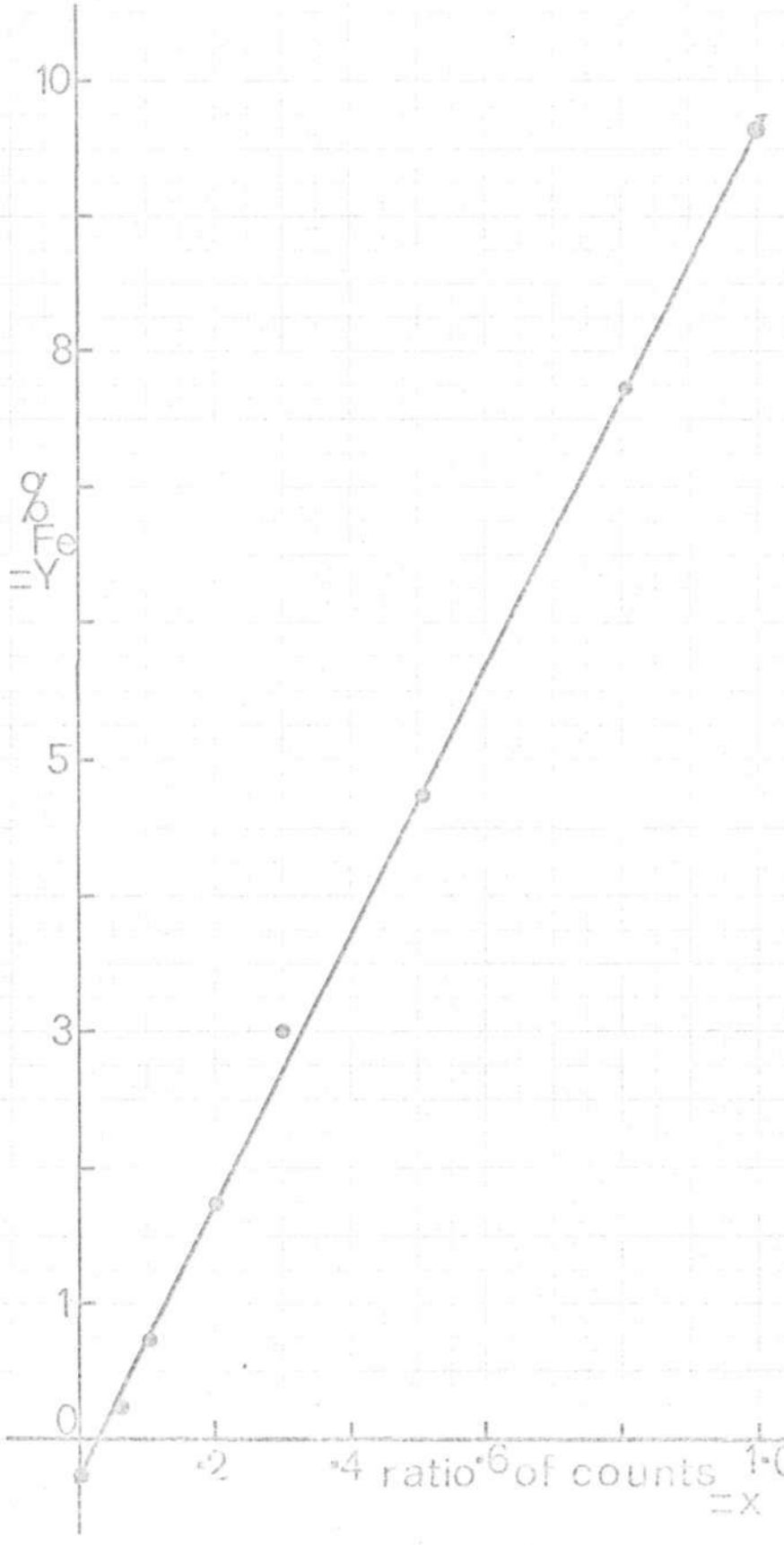
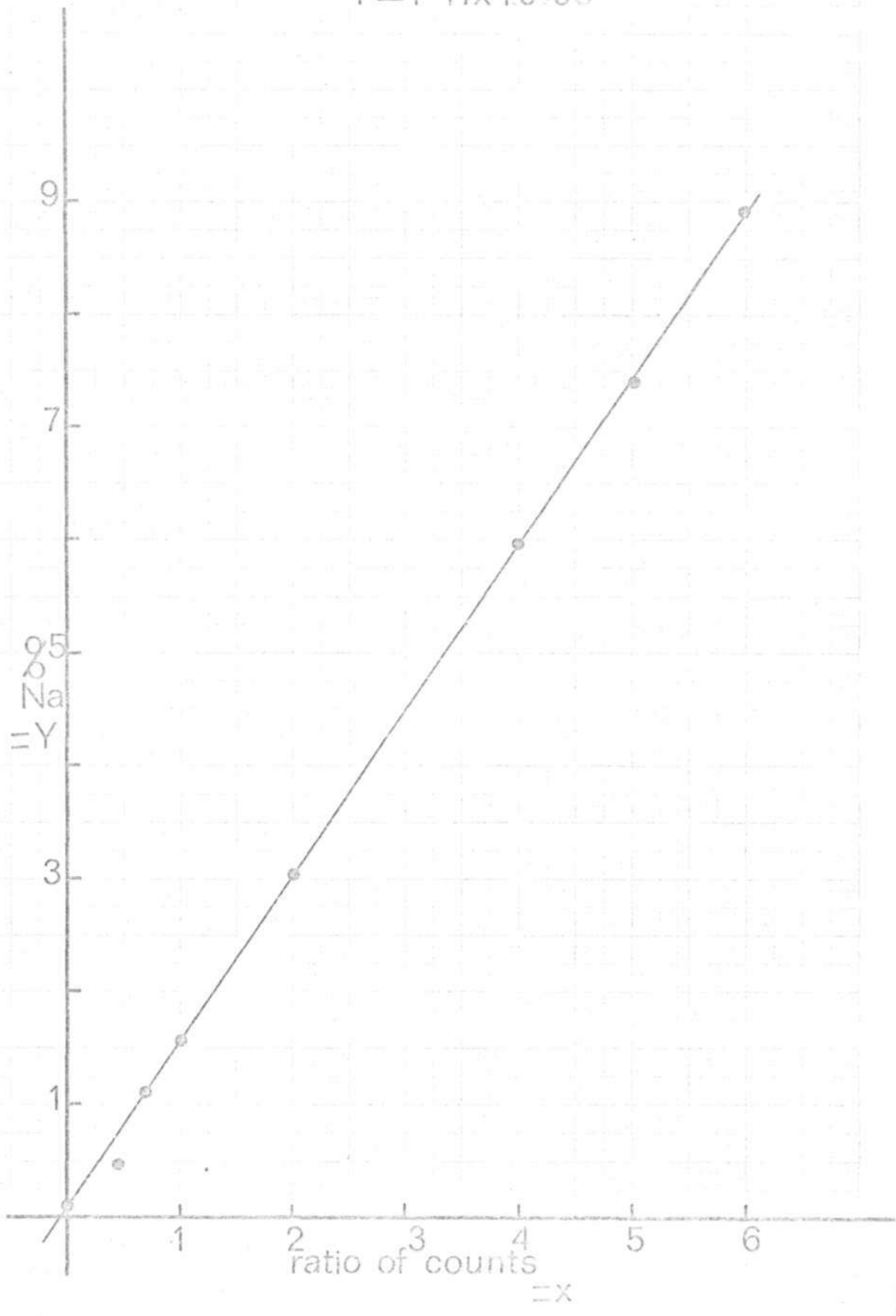


Fig1-2 Calibration curve for Na

$Y = 1.47x + 0.08$



powder was made into pressed powder pellets. The pellets were then analysed for the above elements on the XRF in the same way as the fused beads. /Norrish and Chappell, 1967; Jenkins and Van Gelder, 1968/.

(3) FeO and Fe_2O_3

Ferrous iron was determined by sample decomposition. About 0.2g of sample were placed in plastic bottles and 5 ml of Ammonium metavanadate added, followed by 10 ml of hydrofluoric acid. The mixtures were swirled and after the powders had dispersed, the samples were left to stand overnight. Then 15 ml of mixed acid (200 ml orthophosphoric acid and 450 ml of 50% v/v sulphuric acid) and 15 ml of 4% boric acid were added to the samples. The solutions were then poured into beakers containing 200 ml 4% boric acid, and 10 ml of ferrous ammonium sulphate solution were added followed by 2 ml of sodium diphenylamine sulphonate as indicators. The solutions in the beakers were then tritrated against potassium dichromate solution from a burette. The procedure was carried out at the same time on an empty plastic bottle as a blank. The blank titration was subtracted from the sample titrations and the ferrous oxide percentage calculated thus:-

1 ml standard dichromate ≡ 1 mg FeO = 1000 ugFeO.

Blank titration = y ml.

Sample titration =x ml.

$$\% \text{ FeO} = \frac{(x-y) \times 100}{\text{Sample wt. x } \frac{}{1000 \text{ mg}}} = \frac{(x-y)}{\text{wt. of sample in g x 10}}$$

Ferric iron was then calculated by subtracting the calculated ferrous ion from total iron determined by the XRF method. The results for FeO determination have been

considered to have an error of ± 0.24 and with a lower detection limit of 0.05% FeO (Wilson; 1955).

(4) Rb, Sr, Y and Zr were analysed by pressing the powdered samples on a boric acid back using 2g of sample. The pressed pellets were then analysed using XRF.

(5) Li, Be, Sn, Cu, Pb, Zn and Cd.

About 0.5g of rock powder were placed in 25 ml Teflon dishes and 4 ml of perchloric acid and 15 ml of hydrofluoric acid were added to the dishes in a fume cupboard. An empty dish was included and treated similarly, as a blank. The dishes and their contents were left to stand for three days and then heated for about 8 hours on a water bath until all the hydrofluoric acid had fumed off. The dishes were transferred to a sand bath and the remaining perchloric acid was fumed off under Infra-Red lamps. When the crystal mush was just moist, 2 ml of perchloric acid were again added and the evaporation repeated. When the crystals were again just moist, 15 ml of distilled water were added and the crystals allowed to dissolve and cool. The solutions were transferred into 50 ml volumetric flasks and 1 ml of perchloric acid added, the whole mixture then diluted to volume with distilled water. The solutions were aspirated directly into an Atomic Absorption Spectrophotometer and the sample absorptions were compared to the absorptions of artificial standards. The elements were then calculated thus:-

Sample absorption = x
Blank absorption = y
Net absorption = (x-y)
Higher standard with 'a' ug/ml and absorption h
Lower standard with 'b' ug/ml and absorption l

$$\text{hence ug/ml element} = \frac{(x-y)(a+b)}{h+l}$$

$$\text{and ug/g} = \text{p.p.m} = \frac{\text{ug/ml x dilution}}{\text{wt of sample in g.}}$$

In this case the dilution was 50 and the method has a detection limit of 0.02 p.p.m. for Zn to 1.25 p.p.m. for Sn and a detection range from 2-500 p.p.m. for Be to 25-4000 p.p.m. for Pb. The error of determination is estimated to be about a minimum of ± 1.5 p.p.m. for Be to a maximum of 6.6 p.p.m. for Pb (Belt, 1964, Buckley et al, 1971; Flanagan, 1969 and 1973).

(6) Sn (as Cassiterite)

Owing to the low detection limit of 4000 p.p.m. for Sn in the above method, the tin bearing greisens were analysed by a different method. About 1.0g of rock powder were placed in pyrex test tubes and mixed with 1.0g of ammonium lodide. The tubes were stoppered with a one holed rubber bungs and heated on a bunsen burner with occasional shaking to effect even and gentle heating. The volatile components which vapourised condensed on the cooler parts of the tubes. When no more vapourisation was observed, the tubes were allowed to cool and 10 ml of 10% hydrochloric acid were added to the tubes and shaken to dissolve the sublimates. The tubes were then stoppered and immersed into a water bath at about 70°C to ensure complete dissolution. The tubes were shaken and allowed to settle. The supernatant liquids were then sprayed into Atomic Absorption Spectrophotometers and the results compared to a range of tin standard solutions. The quantitative values were obtained thus:-

$$\text{ug/ml Sn} = \frac{\text{Absorbance of Sample (ug/ml Sn in higher standard + ug/ml Sn in lower standard)}}{\text{Absorbance of higher standard + absorbance of lower standard}}$$

$$\text{then p.p.m. Sn} = \frac{\text{ug/ml Sn x dilutions}}{\text{wt of sample in g}}$$

In this case, the dilution was 10, with an analytical range between 5ug/ml - 200ug/ml Sn and a lower detection limit of 20 p.p.m. Sn. The estimated error of analysis is about $\pm$ 20 p.p.m. (Bowman; 1968).

(7) Sulphur

Sulphur was analysed for only in the greisen samples from Gindi Akwati due to their sulphide content but only five samples gave values from 0.11 to 0.72 per cent with the rest having less than 0.10 per cent S. About 0.1g of rock powder were placed into glass centrifuge tubes and 0.2 ml concentrated nitric acid and 0.6 ml concentrated hydrochloric acid were added to the tubes in a fume cupboard. The tubes were heated to boil for a short time and after cooling 1.0 ml of calcium chloride solution and 5 ml of distilled water were added and again boiled for a short time. The tubes were allowed to cool and 3 ml of ammonia solution and 5 ml of distilled water were added, the tubes shaken and centrifuged to settle the insoluble residues. The supernatant liquids were decanted into 500 ml volumetric flasks and diluted to volume with distilled water. 5 ml of each sample were placed in 2 cm spectrometer cells and about 0.03g of powdered barium chloride were added to the cells using a graduated tube. The cells were shaken to dissolve and mix the barium chloride and after a short time the optical densities of the turbidity in the cells were measured at 650 nm on a Unicam SP 800 spectrometer. Similar treatment was given to an empty tube as a blank and the sulphur content of the samples was calculated thus:-

$$\text{ug/ml S in Sample} = \frac{\text{Absorbance of Sample (ug/ml S in higher std. + ug/ml S in lower std}}{\text{Absorbance of higher std. + absorbance of lower std.).}}$$

$$\% \text{ S in sample} = \frac{\text{ug/ml S in sample x dilution x 100}}{\text{Weight of sample in g x } 10^6}$$

The dilution used was 500 and the analytical range was 0.05 - 20ug/ml S with an estimated error of analysis of about $\pm$ 0.48% S (Shapiro, 1973).

(8) U and Th.

These elements were determined by the non-destructive method of Resonance Neutron Activation Analysis (Meyer, 1971). About 0.4g of rock powder were sealed in polythene sample tubes and irradiated in a cadmium shield for about 5 hours in a 300 Kw Reactor at East Kilbride. As irradiation standards, 10.25mg/ml Th and 10.09mg/ml of U were sealed in polythene tubes and treated as the samples. After a cooling time of 5 days the samples were transferred to accurately weighed sample tubes and re-weighed. For the determination of Uranium, the transitions of ^{239}Np were measured for a fixed time of 60 min. using a Ge(Li) detector and a 400 channel pulse height analyser with a resolution of 1 kev per channel. The intensities of ^{239}Np at 210 kev and 278 kev on channels 472 and 617 respectively were found by passing the signals from the samples via the detector into a channel analyser. The number of counts/channel were teletyped and later reduced by computer to give peak areas corrected for decay and background as well as the standard deviations. After 27 days Thorium was analysed for on the same basis by measuring the intensities of ^{233}Pa between 300 kev-340 kev and channels 550-680 with the best maximum peak on 312 kev

and channel 626. The measurements of ^{233}Pa and ^{239}Np were based on the production of X-rays of these daughter elements on bombardment of the parent Uranium and Thorium during the neutron irradiation thus:-

$$^{238}U(n,\gamma)\ ^{239}U \xrightarrow[23.5\ Min]{\beta^-}\ ^{239}Np \xrightarrow[2.3\ 5d]{\beta^-}\ ^{239}Pu$$

$$^{232}Th(n,\gamma)\ ^{233}Th \xrightarrow[22.1\ min]{\beta^-}\ ^{233}Pa \xrightarrow[27.4d]{\beta^-}\ ^{233}U.$$

After the corrected areas and the standard deviations were found, the Uranium and Thorium contents in the samples were found by comparing with the standards and the calculations were as follows:-

$$\frac{\text{Area of Sample}}{\text{Area of Standard}} \times \text{ug standard} = \text{ug sample.}$$

$$\text{hence } \frac{\text{ug sample}}{\text{weight of sample in g}} = \text{Sample in p.p.m.}$$

For comparison purposes some graphs of counts against channel number were plotted and very good peaks were obtained and areas calculated from these graphs gave good results much closer to values obtained by using areas obtained by computer calculations. Two of such graphs, one for Uranium and one for Thorium are presented here (Fig. 1.3). Generally, for each sample, the values were calculated from 2 peaks and the results gave maximum differences of only 3 p.p.m. This method of determination has been found to have detection limits of Uranium and Thorium at 0.1 p.p.m. in samples of 200 mg (Meyer, 1971, Turkowsky, 1967). The maximum standard deviation found here is however 9.44 for Thorium in a sample containing 257.0 p.p.m.

The methods used for analyses in this study have all been used for a long time and are still being used

Fig 1-3 U. Peak

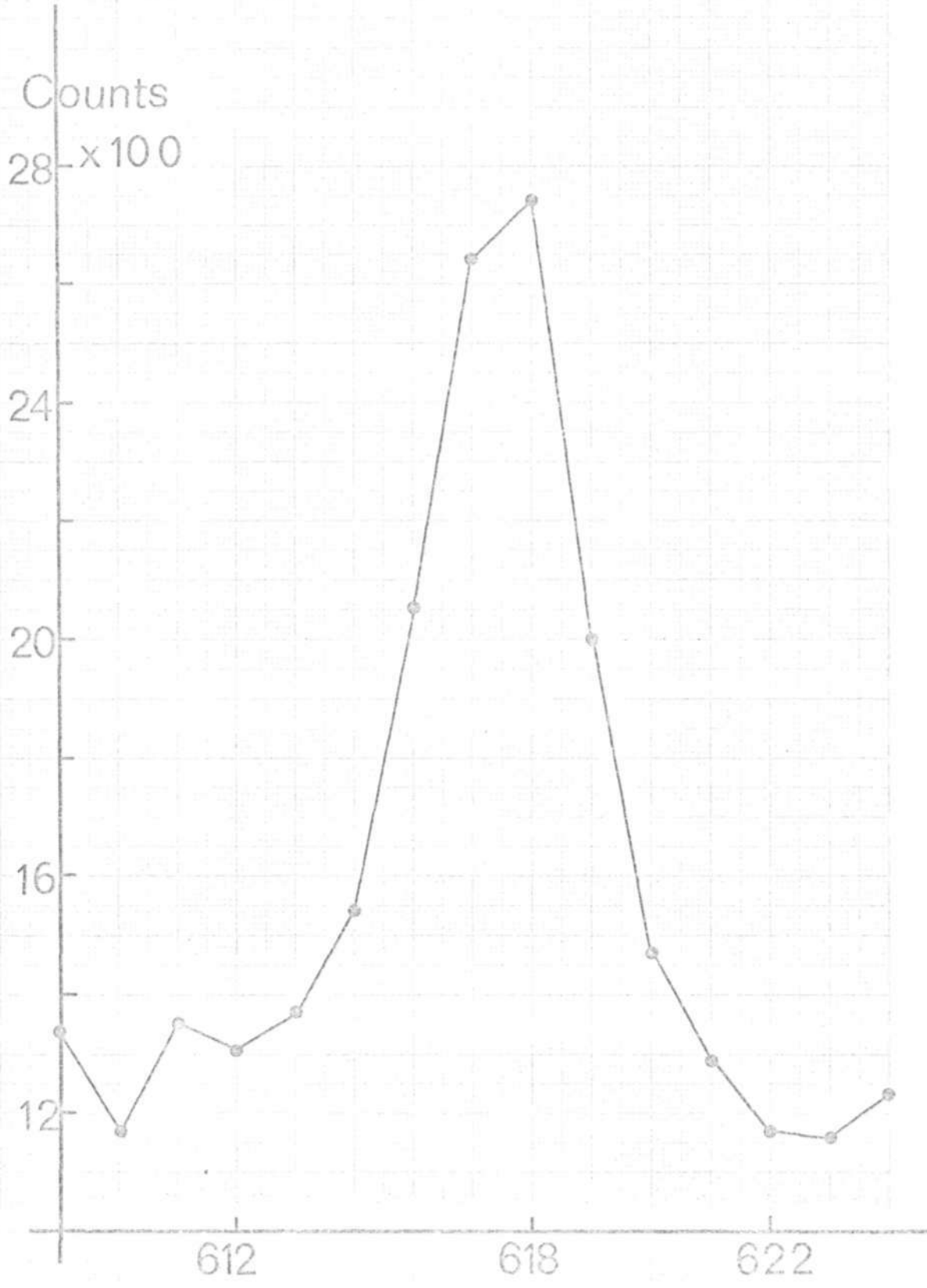
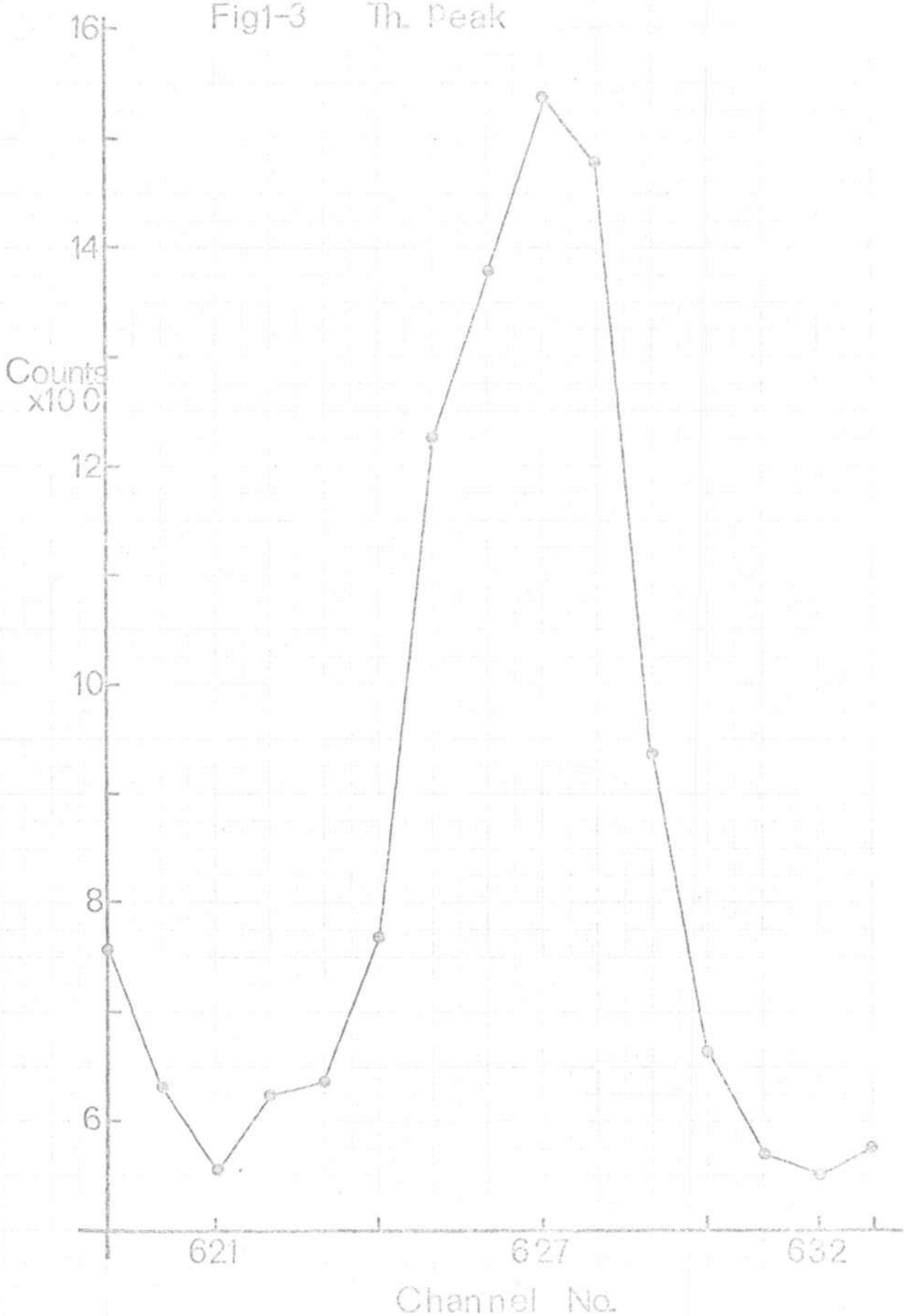


Fig1-3 Th. Peak



extensively. The XRF analyses have been done in the laboratories of the University of Dundee with the assistance of the technician there. These of Rapid Silicate decomposition, Atomic Absorption and a few trace elements on XRF have been done at the University of St. Andrews with the assistance of the technicians, while Uranium and Thorium were determined at the Scottish Universities Research and Reactor Centre with the assistance of Dr. J. Whitley of the Radiochemistry Unit. The results are of high standard and compare very well with published data analysed by the same methods using the same equipment.

These analyses combined with field observations and other petrographic methods of transmitted and reflected light microscopy have been used for the study of the geochemistry and petrology of mineralisation in the three areas of this study (Ririwai, Gindi, Akwati and Dutsen Wai; Fig. 1.1). The individual areas are fully described in the following chapters.

CHAPTER 2

RIRIWAI

General Description

The Ririwai complex occupies an area of about 180 km^2 in the southern corner of Kano State, halfway between Jos and Kano cities. The complex is situated between Latitudes $8^{o}41'E$ and $8^{o}48'E$ and Longitudes $10^{o}41'N$ and $10^{o}48'N$. It has an oval shape (Fig. 2.1), with the longer and shorter axes measuring 14 km and 11 km respectively (Jacobson et al; 1958). The intrusion is a prominent hill massive and rises to about 450 m above the surrounding level plains. The centre of the massif is occupied by biotite granites, surrounded by a broad tract of volcanic rocks. The area has a radial drainage pattern with deep gorges in the steep outer escarpments.

Previous work

Thomas and Vitoria (1922) gave a brief description of the hills with particular attention to the ores and the nature of the veins that contained them. Williams (1923) described the ferruginous capping and its associated fragmental quartz and cassiterite. Russ and others (1927) gave a brief description of the general geology, distinguished between the granites and rhyolites, and gave a short account of the tin mineralisation. Haag (1943) described the area with special emphasis on wolfram and its mode of occurrence. Jacobson (1947) gave a detailed description of the complex in a thesis submitted to the University of London. Furthermore, Jacobson and others (1958) described the different rock types, the petrology and their mineralogy. Turner (1972) has also described its structure and tectonic setting, while

Fig.2-1
GEOLOGICAL MAP OF RIRIWAI COMPLEX





EXPLANATION

riebeckite-granite

fine-grained biotite-granite

medium-grained-biotite granite

amphibole fayalite-granite porphyry

basic rocks

quartz pyroxene-fayalite porphyry

early rhyolites, tuffs and agglomerates

Jacobson and MacLeod (in press) have done more detailed work, modifying and adding to earlier interpretations.

The Complex

The Ririwai complex is a comparatively simple type of ring structure in which two major cycles of magmatic activity have been distinguished (Jacobson et al; 1958), and the intrusion has been found to be about 176 ± 5 my (Van Breemen et al; 1975). The early volcanic cycle which was initiated by ring-fracturing and block subsidence led to the formation of a large caldera in which a great volume of lava and pyroclastic material accumulated. This volcanic activity has been interpreted as being in two stages (Jacobson, 1947). In the first stage, a considerable volume of lava and pyroclastic material was erupted from vents. In the second stage, the rhyolites were entirely intrusive, and appeared as dykes and intrusion breccias in the early lava, and the late rhyolites were emplaced during a further period of fracturing and subsidence of the caldera block. Both types of rhyolites have been intruded by a steeply dipping plug of quartz-pyroxene-fayalite porphyry, which was probably emplaced as a result of further high level cauldron subsidence. This volcanic cycle was followed by a phase of deep-level cauldron subsidence during which the peripheral ring dyke and central granites were emplaced. This granitic cycle is represented by an aster ring-dyke of arfvedsonite-granite-porphyry which has been followed by several phases of biotite and riebeckitic-arfvedsonite-granite. Many rock types were therefore formed during this magmatic activity, which taken together, form the Ririwai ring complex. Jacobson and others

(1958) gave the cycle of volcanic and granitic activity and their summary is reproduced here:

Volcanic Cycle	1.	Early rhyolites, tuffs and agglomerates.
	2.	Late intrusive rhyolites and intrusive breccias.
	3.	Quartz-pyroxene-fayalite-porphyries.
	4.	Basic dykes and semi-conformable basic intrusions.
Granitic Cycle	5.	Arfvedsonite-fayalite-granite-porphyry ring dyke.
	6.	Biotite granites.
	7.	Riebeckite-micro-granites.
	8.	Riebeckite-aegirine granite.
	9.	Albite-riebeckite granite.
	10.	Minor acid dyke rocks.

However, this study is restricted to the central biotite granite and therefore only the biotite granite will be discussed and described further.

The Central Biotite Granite

The biotite granite occupies an area of about 27 km^2 in the centre of the Ririwai ring complex. The biotite granite exhibits several facies and includes smaller microgranitic bodies and dykes which are intrusive into the main biotite granite and have chilled margins. The main biotite granite massif is in turn intrusive into the rhyolites, basic rocks and granite porphyries with many of the microgranite bodies completely enclosed by the volcanic rocks in some places. Towards the contacts with the rhyolites, the biotite granite becomes finer grained, with many knots and streaks of pegmatitic material. The biotite granite contacts with the rhyolites are sharp and well defined. Finger-like bodies and dykes of the biotite granite penetrate into the rhyolites and where such contacts are well displayed, recrystallised zones of the rhyolites can be observed. The biotite granite contacts slightly

dip outwards under the rhyolites, but in most places the contact appears more horizontal. The biotite granite is considered to have been emplaced by cauldron subsidence, the roof being localised by a gently domed cross-fracture, extending almost across the full width of the structure (Jacobson et al; 1958). Gravity measurements have suggested that the biotite granite is a shallow, radial-dipping elongate dome or cupola, extending outwards beyond the confines of the original ring fracture (Ajakaiye; 1968).

The many joint planes predominantly trend between E-W and NW-SE with the minor ones sometimes trending NE, and greisenization is widespread along the joint planes. Quartz veining accompanied by wall rock alteration is widespread in the biotite granite, the greatest development being in the main lode which strikes in a E-W direction and is the most prominent feature of mineralisation in the biotite granite. The main lode and quartz veins have given rise to black zones of greisen and reddened granite. At the eastern end of the main lode, the vein system extends for short distances into the rhyolites with dispersed mineralisation. At present, small scale blasting of these zones in the volcanics is widespread and the local people have won cassiterite in these zones. Some veins occur in the finer grained (microgranitic) biotite granite as well, but such veins rarely contain any ores. One of such microgranites is a sulphurous outcrop and has been blasted, but no ores have been obtained. The abundance of minor intrusions of microgranite and the well developed greisen zones have been interpreted as an indication of proximity to the original roof of the intrusion (Jacobson et al; 1958); and they state

that such features have been noted in granite intrusions of comparable depth of erosion in other parts of the granite province.

The presence of the greisen veins and their coalescence to form a big tin lode has further been used to suggest that the biotite granite has only recently been un-roofed, and the intricate textured variation (coarse grained and microgranitic) and subsequent post magmatic processes are typical of the roof zones of mineralised biotite granites (Bowden et al; 1975).

The main lode

The Ririwai lode is about 5 km long and extends in a E-W direction (Fig. 2.2). The dip of the lode is almost vertical, and it is well exposed on the western side of the biotite granite where it has been extensively worked to depths of up to 9 m in places. The eastern end of the lode is not well exposed, but can be traced easily along the massive quartz-greisen boulders. It is further split into a series of en echelon veins and appears to have been slightly faulted, and the resultant series of veins terminate as tongues and finger-like bodies into the rhyolites.

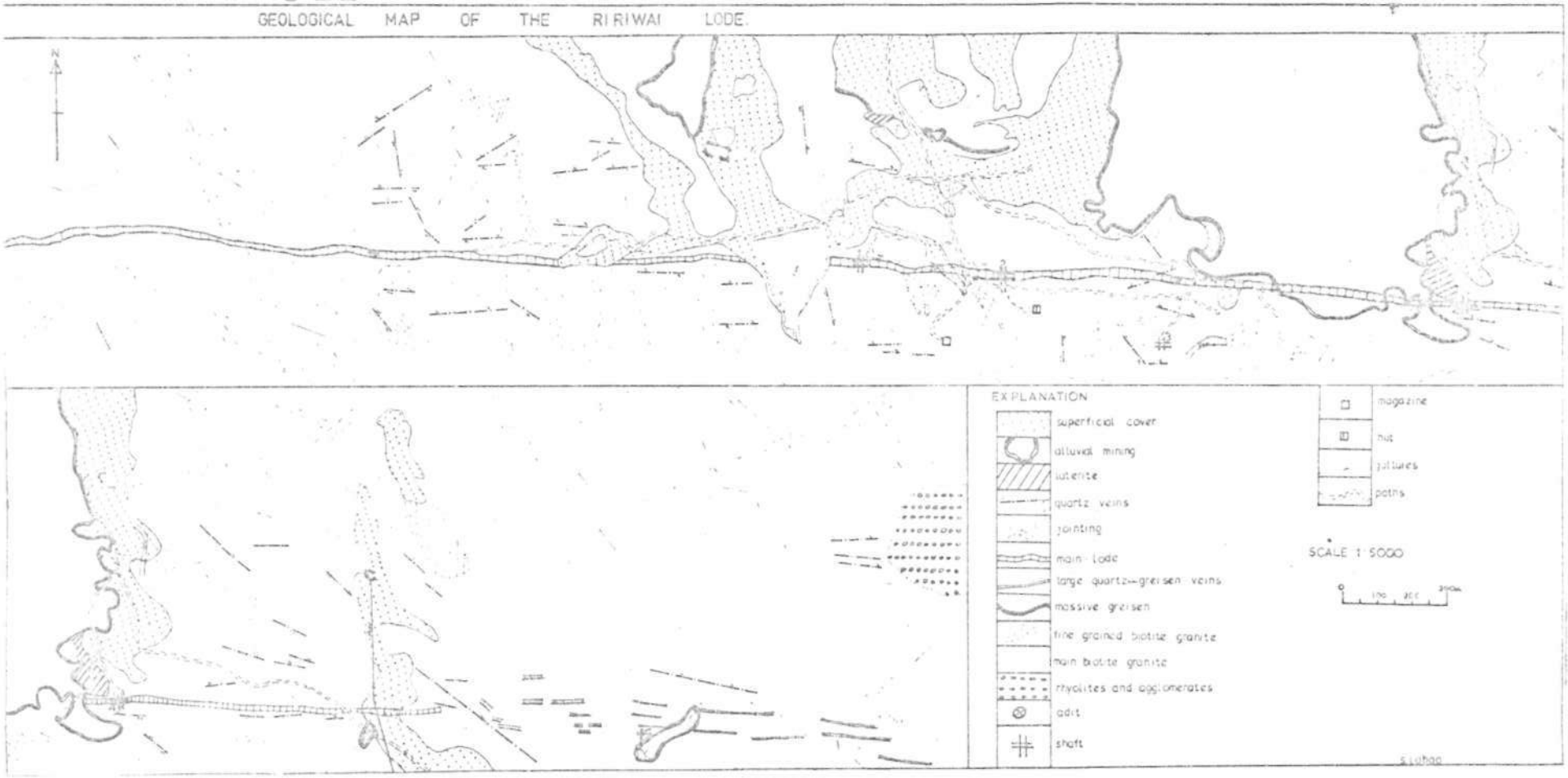
The lode varies in width from 1.5 m to 2.5 m, but its maximum depth has not been ascertained. At present, the Gold and Base mining company is drilling along the lode, and depths of more than 450 m have been reached in the lode. The lode is composed of a central quartz vein containing cassiterite and sulphides. This central quartz with ore is bordered by a zone of dark-greenish greisen which varies in width from a few cms in places to more than 1 m wide, on

Figure 2.2 is a detailed map of the Tiriwai lode and the surrounding rocks and major joint directions. The lower portion of the map is the eastern end of the lode and has been drawn so that the west end overlaps with the east end of the upper portion to show the continuity. The scale of 1:5000 as stated is inaccurate since the map has been reduced by photography and so only the representative scale is valid.

1cm = 250m.

Fig. 2-2

GEOLOGICAL MAP OF THE RIRIWAI LODE.



both sides of the central quartz. Smaller veins of quartz branching from the central vein into the bordering greisen are very common particularly at the western end (Fig. 2.3). The greisen zone passes laterally into reddened granite on both sides of the lode, and the reddened granite zone may vary from 1 m to more than 5 m in width. This reddened granite zone in turn grades into the unaltered biotite granite. The junction between the greisen and reddened granite is irregular but sharp in some places. Similarly the junction between the reddened granite and unaltered granite is irregular but may be sharp in some places. The total effect therefore is that of a lateral zoning and is persistent on the west end of the lode (Fig. 2.3). A similar type of zoning has been described from Casapalca, Peru (Kinstry and Noble; 1932); where the veins that traverse greyish-green porphyry intrusives are outlined by white, pink, green and purplish alteration zones that are in a sequential pattern from the veins outwards in that order.

The veins

A braided series of quartz veins, nearly vertical with zones of greisen and granite reddening occur associated with the main lode (Fig. 2.4). The veins vary in size and numbers from place to place, but concentrate more at the two ends of the lode where the lode approaches granite ridges. The veins are usually separated from one another by large portions of unaltered granite. The quartz veins are lenticular, with numerous branches and may range from stringers to a width of about 8 cm exhibiting a crude comb-like structure (Fig. 2.4). The veins are massive in some

Figure 2.3 is a plan of a section of the lode at the west end showing the various zones of the altered wall rock. The centre is massive quartz with ore minerals, which is bordered by massive greisen, which is bordered by reddened granite, in turn bordered by unaltered granite. Much of the section has been worked to depths of more than 5m.

Scale: 1cm = 2.5m.

Fig. 2-3

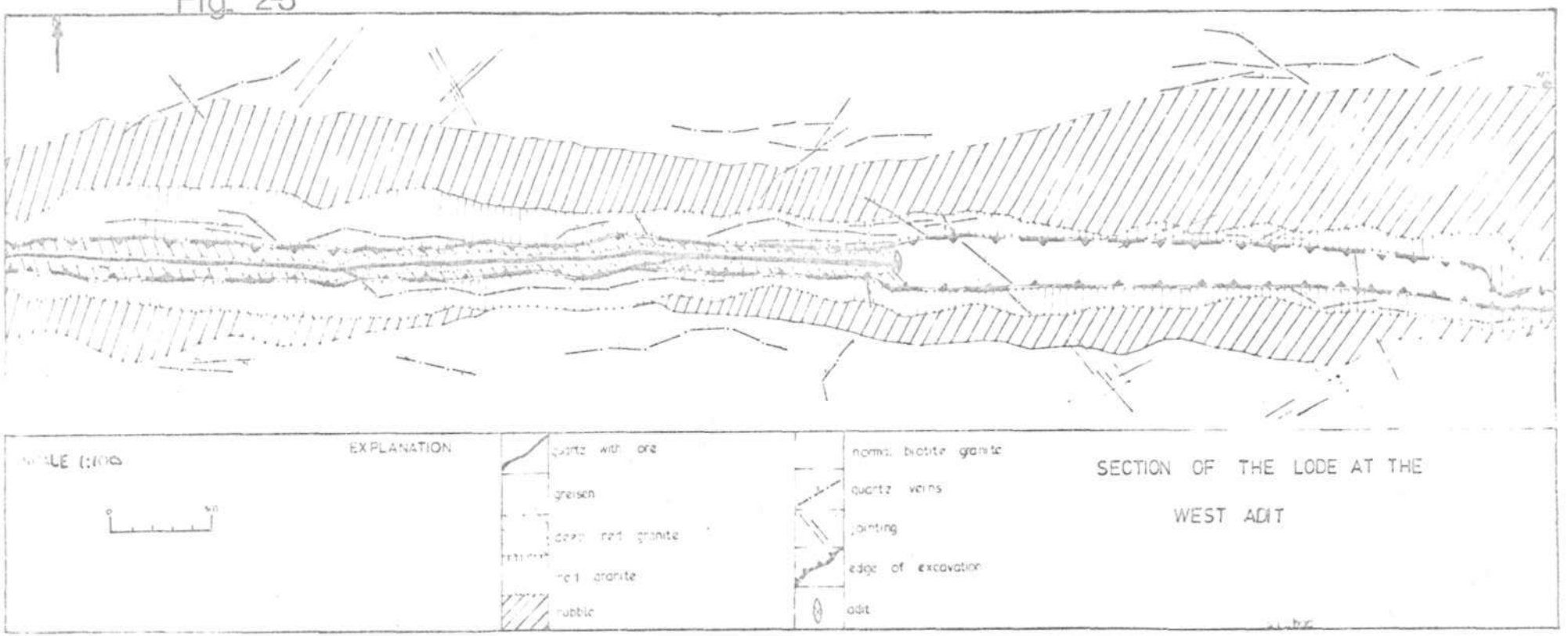

EXPLANATION
quartz with ore
gneiss
red granite
rubble
normal biotite granite
quartz veins
jointing
edge of excavation
adit
SECTION OF THE LODE AT THE
WEST ADIT

Figure 2.4 is a map of a zone showing the typical vein system adjacent to the main lode. The thicker veins are those that have similar zonation of wall-rock alteration to the main lode i.e. a centre quartz sometimes with ore minerals, bordered by massive greisen which is bordered by reddened granite, in turn bordered by unaltered granite. Only the veins on one side of the main lode are shown here.

Scale 1cm = 2.5m.

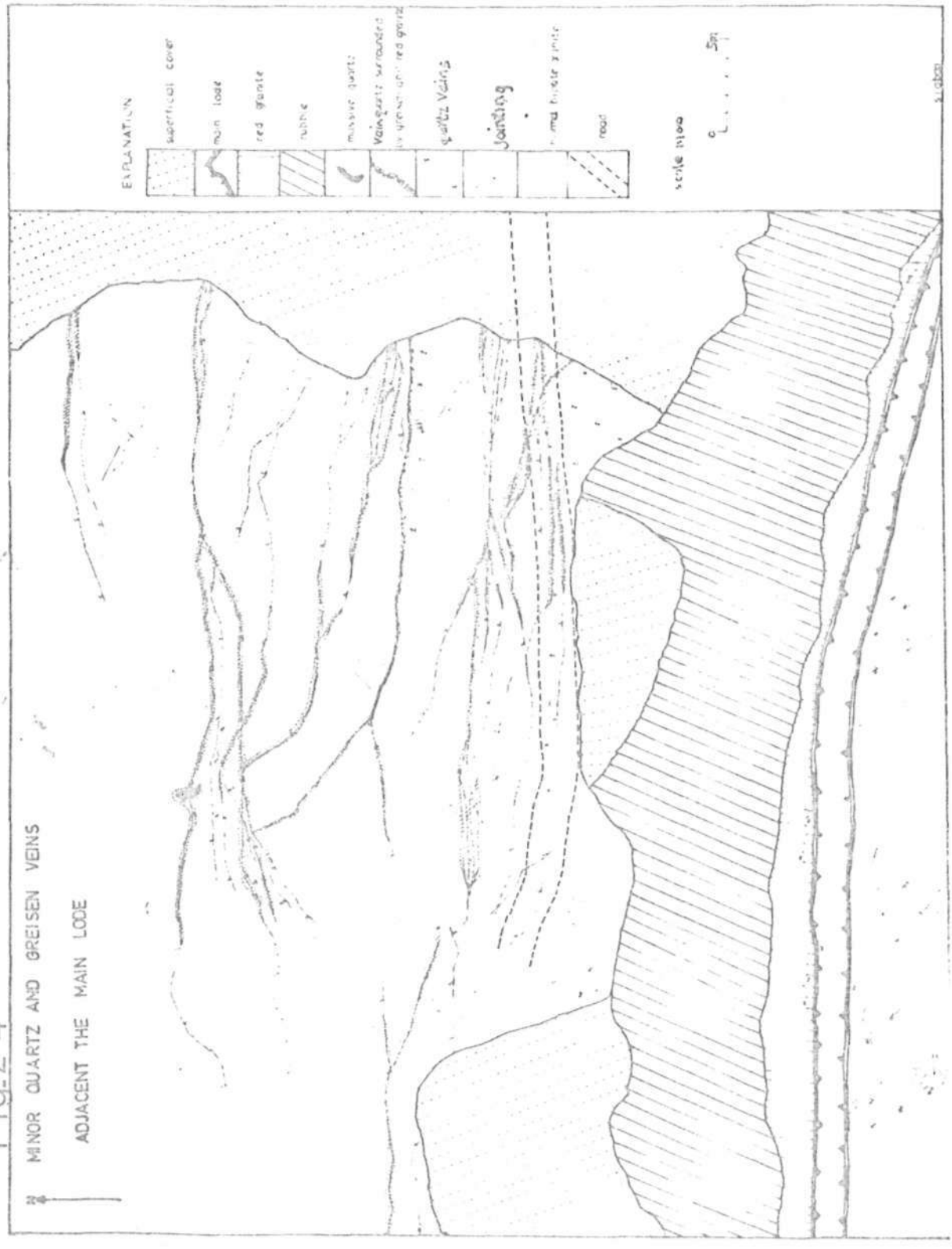


Fig 2-4

MINOR QUARTZ AND GREISEN VEINS ADJACENT THE MAIN LODE

places but cavities also occur, usually containing quartz, mica, a clay mineral and sometimes cassiterite. The contacts between the veins and the greisenised granite are sharp, and where the veins tend to be massive, similar zoning as in the main lode can be observed.

The quartz veins are undoubtedly fissure filling veins. The vein forming fluids must have been injected into a braided series of narrow fissures which were further forced apart by the hydrostatic pressure and the wedging effect of the ore fluids. The formation of the quartz veins was accompanied by extensive alteration of the wall-rock, but quartz veins with only slight greisenisation of the wall-rock as well as greisenised fissures without a quartz filling are present. This indicates that the extent of greisenisation is not directly related to the size of the adjacent quartz veins, and may infer that the greisenisation of the wall-rock may have taken place slightly earlier than the filling of the channel ways with quartz and ores. It is possible that the fissures were opened for some time and quartz filling and ore deposition took place over a period of time. However the formation of the veins, greisens and reddened granite were closely connected and the quartz veins are typical fissure veins (Lindgren; 1933).

2.1 Petrology and Mineralogy

The central biotite granite with which the Ririwai lode is associated has a variable texture and colour. It is a medium to coarse grained rock. The larger proportion of the granite intrusion is pinkish, but towards the eastern part of the lode, a whitish variety, much more even textured

occurs. Unlike the pinkish granite which has clusters of biotite, the whitish variety contains individual flakes of biotite and small spots of iron staining can be abundant and easily observed in hand specimen. Although similar oxide staining may be present in the pinkish variety, it may not be easily seen in hand specimen.

Biotite Granite

In thin section, the biotite granite contains large crystals of quartz, orthoclase and microcline microperthites. The large quartz crystals occur in clusters giving an intermittent grey-white-dark matrix. The quartz is generally clear and lacks fractures and strains with little or no inclusions. Some sections reveal graphic intergrowths of quartz with orthoclase and a few pseudomorphs of quartz after microcline-microperthites can be observed.

The orthoclase microperthite crystals are anhedral, irregular, and in some cases patchy. The cloudiness of the orthoclase perthites can be extensive and is attributed to kaolinisation. Red brown gels and clots are also associated with the microcline and perthites. Albite sometimes appears as narrow rims around the borders of the perthites. In some sections (L13-315; L13-411 and L13-440), individual crystals of well twinned albite occur and are particularly abundant in L13-411. The albite is likely late deuteric, developed during the albitization process. Several of the albite crystals have extinction angles between -3° to -15° and the compositions therefore lie between $Ab_{90}\ An_{10}$ and $Ab_{95}\ An_{5}$ by the Michel Levy method (Kerr; 1959).

The biotite of the granite is either dark greenish or brown. The biotite may either be pleochroic from deep brown to pale or straw yellow or it may be pleochroic from

pale green to dark greenish brown. Some sections may be pleochroic from dark brown to opaque. Some of the dark brown biotite have developed pale green overgrowths and extensive alteration and replacement has affected the biotite of the rock. The biotite may sometimes be associated with abundant iron oxides and fluorite. A few zircon crystals sometimes occur close to the biotite boundaries, and in association with columbite and xenotime. In such areas, much of the biotite may contain radioactive haloes as well as replacement or enclosed crystals of fluorite particularly along cleavage planes. Some optical properties determined on the biotite are given below (Table 2.1).

Table 2.1 Optical properties of micas from Ririwai

Optical Property	Sample L13-10	L13-411	4	RS 2	RS 3
n	1.602-1.609	1.598-1.603	1.602-1.605	1.590-1.621	1.60-1.605
2V	5-10°	3-8°	n.d.	30°	30-45°
Ext z a	2-4°	0-3°	n.d.	3-6°	4-8°
X	pale brown	green	n.d.	pale green	pale-yellowish green
Y	dark brown	greenish brown	olive green -yellow	yellowish brown	deep green
Z	nearly opaque	dark green brown	dark olive green	brownish green	pale brown
Absorption	X≺Y≺Z	Z≺Y≺Z	Y≺Z	X≺Y≦Z	X≺Y≺Z

L13-10. Biotite, from sample at 10m depth in the Biotite granite
L13-411. Biotite, from a sample at 411m depth in Biotite granite
RS 2. Mica, from greisenised granite on surface.
RS 3. Mica, from greisen from blasted boulders.
} determined by S. Abaa

4. Green mica (ferrophengite) from tin-bearing greisen zone of Ririwai Lode. X700, taken from Jacobson et al. (1958) P.15.

The most common accessory mineral in the biotite

granite is fluorite. Massive fluorite occurs always associated with biotite. Zircon is sometimes present while iron oxides may locally become abundant around the biotite crystals. Two of the sections examined contained crystals of sphalerite in relatively unaltered granite. Other accessory minerals in the rock include thorite, columbite and xenotime.

Quartz, orthoclase and microcline-microperthites form the bulk of the biotite granite composition. Quartz forms about 37 per cent modal volume of the rock while feldspars form about 55 per cent of the rock and biotite 2.5 per cent (Table 2.2). Biotite may have crystallised first followed by feldspars. The late deuteric alteration must have modified the simple exsolution perthite texture resulting in the irregular, patchy replacement perthites, while late deuteric albite has formed narrow rims around the borders of the perthites. This deuteric effect and some late hydrothermal action caused recrystallisation with microcline and finely twinned clear euhedra albite introduced. This may have been the period of introduction of fluorite. It is thought that the sphalerite developed in relatively unaltered granite may have been dispersed in the rock at this recrystallisation period, together with the other accessory minerals of columbite, xenotime and thorite. The iron oxides associated with the biotite may be a replacement product of the biotite and other minerals, while the common haloes in biotite are radioactive cores caused by bombardment from the zircon crystals containing some radioactive material.

Reddened Granite

The reddened granite is easily identified as derived from the biotite granite. Its colour varies from pinkish at the western end of the lode to a deep brick red at the eastern end. Its texture is much the same with that of the original biotite granite, but contains small dots and clots of a green mica which may have arisen due to incipient greisenisation.

Table 2.2. Modal analysis of rocks from Ririwai

Sample	L13-10	L13-190	L13-315	L13-411	L13-440	RS 1	RS 2
Quartz	35.5	35.6	36.9	33.7	34.8	30.1	43.6
Orthoclase-microperthite	54.7	55.8	54.1	52.3	52.4	62.9	20.8
Plagioclase	4.9	4.3	7.4	12.3	10.8	0.7	trace
Biotite	2.3	2.8	1.7	1.1	1.2		
Mica						3.1	16.5
Fe oxides	0.9	trace	0.4	0.2	0.2	4.3	0.8
Fluorite	0.5	0.3	0.8	1.3	0.9	0.4	1.7

Numbers with L13 are biotite granites, and the numbers after L13 indicate the depth in metres from which the sample was taken.

RS 1. Reddened granite.

RS 2. Greisenised granite.

Modal analysis by S.I. Abaa 1976.

In thin section, the reddened granite consists of potash feldspars which are highly mottled and the orthoclase-micro-perthitic texture in the unaltered granite has been destroyed, while small amounts of mica and fluorite are present.

The general appearance is that of recrystallisation and reconstitution. Fine specks and dots of iron oxides and red jells are also present. The fine specks of iron oxide are usually crowded around and in the reconstituted feldspars. The red gels and crowded iron oxides are possibly the cause of the red colour of the feldspars, giving the whole rock its pinkish and brick red colours.

From the modal analysis (Table 2.2) the amount of quartz has dropped slightly in the reddened granite, while the modal volume percentage of feldspars has increased remarkably. The plagioclase (albite) of the unaltered granite has been completely eliminated and sections with remnants of the original feldspars have been highly sericitised. The biotite of the original granite has been partly replaced and chloritised while a new mica is beginning to develop. The abundant iron oxides are due to haematisation (Wilson; 1972) and becomes more intense adjacent to the lode. This type of wall-rock reddening associated with tin mineralisation has been reported, and in most cases, there is a similar feldspar reconstitution and enrichment in oxides or bleaching formation of a new mica or replacement of biotite by chlorite and/or fluorite as well as sericitisation (Wilson, 1972; Hall, 1971; Noble and Kingsley; 1932).

Greisen

The greisen proper is dark green while the greisenised granite is rather grey with tints of pink which indicates that the greisen is a product of the reddened granite. This implies that the biotite granite underwent a progressive alteration through reddened granite to greisen. It can thus be concluded that ore fluids caused alteration of the wall-rock and the intensity of alteration increased towards the

fissures along which the fluids migrated, until ores were deposited in the fissures. Thus the reddened granite may have been formed before the greisen which in turn was formed before the central quartz and associated ores (Fig. 2.5). The minerals that can be easily recognised in hand specimen in the greisen are quartz, mica, galena, sphalerite, cassiterite and sometimes fluorite, while topaz is rare and may not be seen even in thin section. Impregnations of quartz, sphalerite and galena are abundant in the greisen associated with the main lode, while narrow zones of greisen associated with adjacent veins occasionally contain large well developed individual crystals of quartz (Fig. 2.4). The greenish greisen appears porous with abundant small cavities sometimes lined with acicular quartz, green mica and grains of cassiterite or some sulphide ore. At contacts with the central vein quartz and the greisen, dark green or greyish-black mica segregations can be found.

In thin section, the greisen consists mainly of large clear anhedral crystals of quartz and two varieties of mica. Chlorite occurs as a secondary mineral in the form of narrow fingers around the mica crystals. Chlorite can also be observed in small cracks in quartz and feldspar crystals in the greisenised granite and along cleavage planes of mica in the greisen. In some sections of the greisen, iron-rich gels and small pale yellow patches of chloritic material are found associated with mica. The feldspars have been initially eliminated in the greisen, while the green mica and quartz show partial replacement by late galena and sphalerite. A modal analysis of the greisenised granite (Table 2.2) shows a marked increase in quartz, a large decrease in feldspars, a

Figure 2.5 is a plan of the central quartz of the main lode containing ore minerals. P1, P2, P3 and P4 are the individual traverses across the quartz-ore zone. If lines are drawn to join corresponding zones from P1 to P2 to P3 to P4, then the thicknesses of the zones can be seen to vary along the strike of the lode, while in some traverses along the strike, some of the zones disappear.

Scale 1 cm = 2.5 m. The scales stated on the map are invalid due to the reduction of the map.

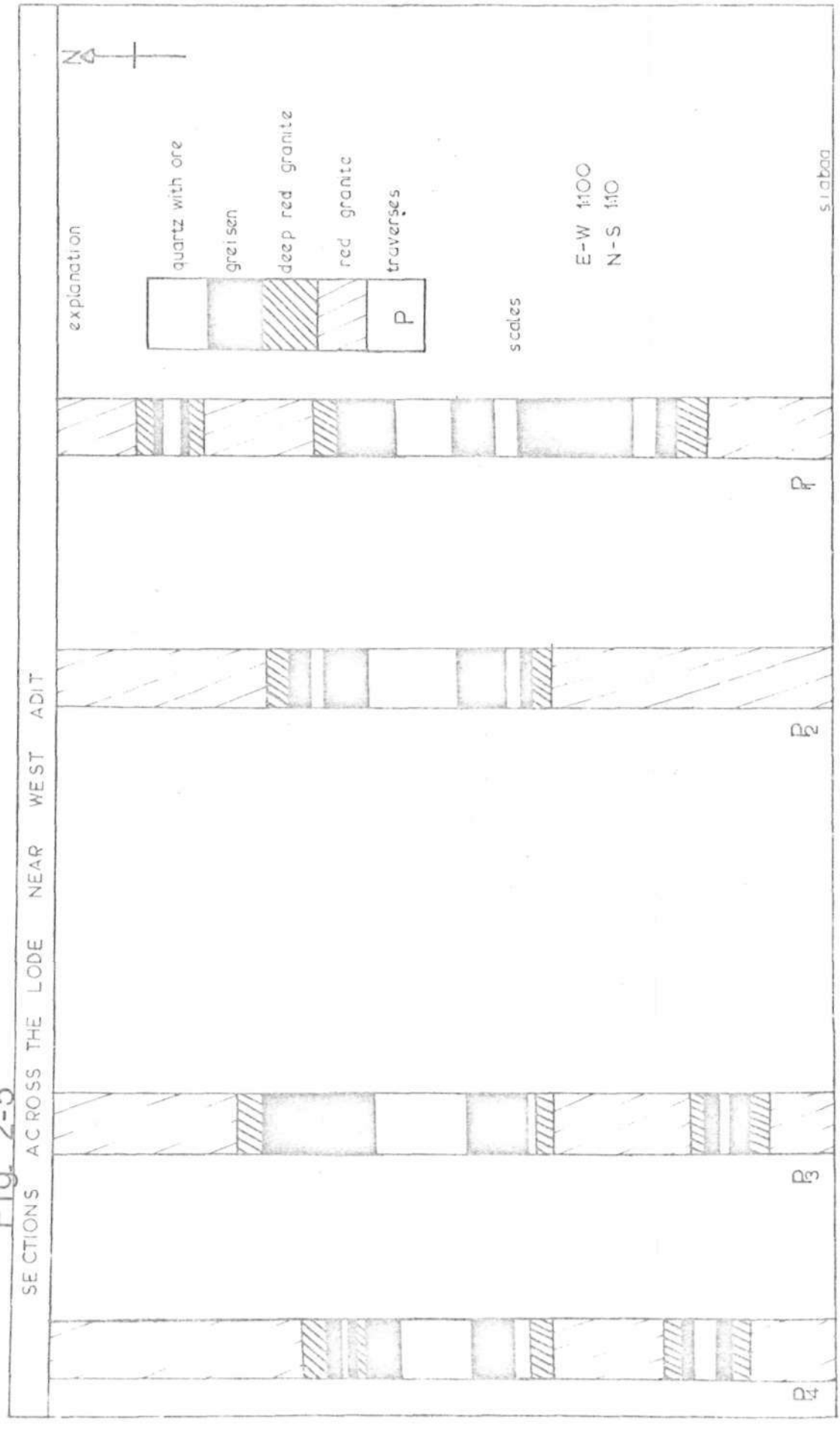


Fig. 2-5
SECTIONS ACROSS THE LODE NEAR WEST ADIT

large increase in the mica and an increase in fluorite over the unaltered biotite granite.

The mica of the greisen

The greisen contains two main varieties of mica with little flakes of biotite remaining in some sections. The paler green mica is pleochroic from pale-yellow-green to deep green or brownish green, while the second variety is pleochroic from colourless to pale brown (Table 2.1). Certain sections of the mica are radiating and exhibit some zoning with weak birefringence. The cores are usually pale green or pale yellow, while the outer zone is dark or greyish. The absorption is usually $X \angle Y \angle Z$ with 2V between 30° and 45° and the mica is thought to be an iron rich member of the octophyllite group (Bowden and Turner, 1974). Some optical properties determined on the greisen micas are given (Table 2.1) and the chemical composition of a mica from this greisen is counted (Table 2.3), together with two micas from Cligga Head granite, Cornwall (Hall; 1971). The mica is rich in ferrous oxide, potash, fluorine and lithia, and is similar in chemical composition to the protolithionite in the unaltered granite from Cligga Head, but the mica from the Cligga Head greisen is muscovite.

It is certain that the Ririwai greisen has been formed by the conversion of the feldspars of the original biotite granite to green mica and secondary quartz as well as the conversion of the biotite of the original rock. Furthermore the replacement of mica and quartz by ores of lead and zinc and the introduction of new minerals namely galena, sphalerite, iron oxides, cassiterite, fluorite, chalcopyrite and other sulphides produced the final alteration product; the greisen.

Table 2.3. Chemical analysis of micas.

	1	2	3	4
SiO_2	37.38	38.50	42.24	46.02
Al_2O_3	11.89	23.70	19.62	29.29
Fe_2O_3	4.38	0.68	2.02	2.69
FeO	28.65	17.15	18.64	4.02
MgO	0.22	2.09	0.08	0.16
CaO	0.16	0.60	0.11	0.35
Na_2O	0.39	0.30	0.14	1.08
K_2O	8.78	9.39	8.84	10.39
H_2O^+	1.84	1.69	2.35	3.87
H_2O^-	0.67	0.00	0.48	0.00
CO_2	0.08	n.d.	0.05	n.d.
TiO_2	1.84	1.55	0.18	0.00
Cl	0.09	n.d.	0.02	n.d.
F	4.36	3.62	5.02	1.29
S	0.03	n.d.	0.02	n.d.
MnO	0.41	0.59	0.30	0.50
Li_2O	0.77	1.21	1.90	0.25
Rb_2O	n.d.	0.48	n.d.	0.31
	101.94	101.48	102.01	100.22
Less O	1.86	1.52	2.11	0.54
Total	100.08	99.96	99.90	99.68

1). Biotite (Lepidomelane) from biotite granite, Ririwai.

3). Green mica (ferrophengite) from greisen zone, Ririwai.

1 and 3 taken from Jacobson *et al.* (1958) P15.

2). Protolithionite from unaltered granite, Cligga Head granite, Cornwall.

4). Muscovite, from greisen zone Cligga Head granite, Cornwall

2 and 4 taken from Hall, (1971) P225.

2.2. Geochemistry

The most significant feature of the Nigerian Younger Granite Province in which Ririwai biotite granite occurs is that slight differences in the atomic proportions of Na, K, and Al can produce striking changes in the mineralogical composition of the rocks (Bowden and Turner; 1974), with a general tendency for low Ca and Mg contents. It has been recognised that certain trace elements like Li, and Rb concentrate in the biotite granite as well as other rock types, while there is a marked depletion in Sr. and Ba, and a less intense depletion of Sc, Cs and V relative to average granitic compositions (Bowden and Van Breemen, 1971; Bowden and Turner, 1974).

Major Element Chemistry

14 samples of the biotite granite were selected from Core No. L13 up to a depth of 440 m and analysed for major elements and the results of the analyses are presented (Table 2.4). No detailed description of the cores is given and the cores did not intersect the lode nor any greisen zones. Two of the cores (L13-411 and L13-440) however appeared altered with much of the quartz leached out. The samples have become more porous with little vugs, but the colour of the original granite is still preserved. From the analyses the following characteristics have been observed:-

1. With the exception of two samples (L13-411 and L13-440), the silica content of the rocks is relatively constant with a range of 73.87-76.17 percent SiO_2 and a mean of 75.28 percent. The other two samples show lower values of silica at 68.12 and 69.29 percent respectively.

	L13-10	L13-26	L13-115	L13-145	L13-150	L13-[illegible]	L13-205	L13-256	L13-290	L13-310	L13-315	L13-327	L13-411	L13-440
SiO_2	75.23	74.89	75.96	75.19	75.17	76.10	74.56	73.87	76.17	74.78	75.84	75.59	68.12	69.29
TiO_2	0.08	0.10	0.12	0.11	0.11	0.12	0.14	0.16	0.13	0.12	0.11	0.12	0.09	0.11
Al_2O_3	12.80	12.61	12.83	12.28	12.40	11.09	12.44	12.31	12.03	12.83	12.80	12.57	16.13	15.02
Fe_2O_3	0.42	0.66	0.36	0.37	0.35	0.59	0.38	0.54	0.61	0.60	0.41	0.37	0.51	0.78
FeO	1.15	1.09	1.23	1.47	2.28	1.40	1.67	2.03	1.33	1.15	1.11	1.28	1.48	1.54
MnO	0.04	0.04	0.05	0.06	0.06	0.04	0.05	0.06	0.04	0.18	0.05	0.05	0.08	0.08
MgO	0.14	0.09	0.08	0.09	0.03	0.09	0.11	0.17	0.17	0.05	0.10	0.14	0.11	0.13
CaO	0.49	0.48	0.57	0.46	0.40	0.41	0.77	0.59	0.43	0.48	0.40	0.34	0.52	0.42
Na_2O	4.14	4.22	4.42	4.84	4.53	4.07	4.15	4.75	4.40	4.28	5.05	4.36	9.95	8.43
K_2O	4.62	4.97	4.07	4.66	4.81	4.45	5.01	4.92	4.46	4.77	3.82	4.53	2.46	2.39
P_2O_5	0.05	0.03	0.03	0.04	0.04	0.04	0.06	0.03	0.02	0.05	0.04	0.05	0.06	0.06
H_2O^+	0.39	n.d.	n.d.	n.d.	0.41	n.d.	0.46	n.d.	0.15	n.d.	0.24	0.17	0.21	0.18
H_2O^-	0.07	n.d.	n.d.	n.d.	0.17	n.d.	0.09	n.d.	0.04	n.d.	0.05	0.04	0.03	0.04
F	0.32	0.21	0.22	0.23	0.21	0.21	0.23	0.39	0.14	0.26	0.17	0.24	0.26	0.32
	100.04	99.39	99.94	99.80	100.97	98.61	100.12	99.83	100.12	99.55	100.19	99.85	99.96	98.79
Less O	0.09	0.03	0.13	0.04	0.17	0.04	0.15	0.05	0.03	0.05	0.11	0.07	0.41	0.23
Total	99.95	99.36	99.81	99.76	100.80	98.57	99.97	99.78	100.09	99.50	100.18	99.78	99.55	98.56
Quartz	30.06	28.12	31.34	27.10	26.46	32.20	26.54	24.83	29.72	28.84	28.55	30.07	7.15	-
Orthoclase	25.53	29.26	22.53	27.43	26.60	26.92	29.14	28.80	25.91	26.93	21.20	24.97	13.85	-
Albite	36.94	38.29	39.89	39.61	38.61	35.07	36.98	38.22	39.35	38.76	44.98	39.18	70.06	-
Anorthite	1.81	0.80	2.33	-	-	Dip. 0.15	0.52	-	-	1.65	0.98	0.94	Dip. 0.38	-
Actinolite	-	1.58	-	2.46	1.98	1.80	3.59	3.27	2.33	-	0.53	-	1.97	-
Riebeckite	-	-	-	1.94	1.80	3.16	-	2.83	0.27	-	-	-	2.54	
Biotite	2.57	0.67	2.62	0.28	2.15	-	0.39	0.54	0.73	2.40	1.90	2.92	-	
Corundum	0.35	-	0.38	-	-	-	-	-	-	0.03	-	0.17	-	
Sphene	0.17	0.21	0.25	0.23	0.23	0.26	0.29	0.34	0.27	0.25	0.23	0.25	0.18	
Magnetite	0.44	0.70	0.38	-	-	-	-	-	0.58	0.63	0.43	0.39	-	
Apatite	0.10	0.06	0.06	0.08	0.08	0.09	0.12	0.06	0.04	0.11	0.08	0.10	0.12	

L 13 refers to core number and numbers after L13 refer to depths from which sample [illegible]aken. Barth mesonorms calculated by computer.

Analyst: S.I. Abaa (1976).

2. The alumina content is also relatively constant ranging from 11.09-12.83 and a mean of 12.42 per cent. The exception again is in the altered samples, which have higher Al_2O_3 range from 15.02-16.13 per cent and a mean of 15.58 per cent. Sample L13-190 has a silica content of 76.10 per cent and 11.09 per cent alumina. This sample and the other two (L13-411 and L13-440) give an indication that as the silica content of the biotite granite increases, the alumina content decreases.

3. The total iron (FeO and Fe_2O_3) also increases as alumina increases and silica decreases. But in all the samples the ferrous ion is higher than the ferric ion and the ratio of Fe^{3+} to Fe^{2+} ranges from 1:2 to 1:4.

4. Na_2O is relatively constant with a range from 4.07-5.05 per cent except in the altered samples where there is an increase in Na_2O with a range of 8.43-9.95 per cent. There is however, a general tendency for Na_2O to increase as the silica content decreases.

5. K_2O is also relatively constant but there is a tendency for it to decrease as Na_2O increases, and there is a near proportionate relationship between K_2O and Na_2O, and the ratio of K_2O to Na_2O is always about 1:1. The exception here again is in the two samples (L13-411 and L13-440) where Na_2O is much higher and the ratio of K_2O to Na_2O becomes 3:1. However the general trend is for K_2O to decrease as Na_2O and Al_2O_3 increase and SiO_2 decreases.

6. CaO is low in all the samples analysed with a range of 0.37-0.59 per cent and seems to show no relationship with neither the other major elements nor the fluorine content.

7. Both MgO, MnO and P_2O_5 are very low with a range of 0.03-0.18; 0.04-0.09 and 0.02-0.06 per cent respectively.

8. Cl is virtually absent in all the samples while the amount of lattice water (H_2O^+) is relatively constant ranging from 0.15-0.56 per cent. Fluorine is present in all the analysed samples with a range from 0.14-0.39 per cent.

9. The agpaitic coefficients $\left(\frac{\text{mp } Na_2O + \text{mp } K_2O}{\text{m.p. } Al_2O_3}\right)$ of the samples range from 0.85-0.92 except in the two altered samples which have a range of the ratio from 1.13-1.19.

Furthermore the modal volume percentages of Orthoclase-microperthites, albite, biotite and fluorite (table 2.2) have been plotted against silica content instead of the usual oxide variation diagrams. The results (Figs. 2.6a-d) show that as the silica content increases:-

1) the modal volume percentage orthoclase-microperthites also increases. This increase is negligible if only the unaltered biotite granites are considered. The two agpaitic samples plot in the low region of the orthoclase-microperthite while the normal granites plot in the high region and actually do not show this trend on their own.

2) The modal volume percentage albite decreases. This decrease is only observed when the agpaitic samples are considered with the normal biotite granite.

3) the modal volume percentage biotite also increases.

4) the modal volume percentage fluorite decreases.

The modal volume percentages of these minerals and quartz were also plotted against the agpaitic coefficients of the samples (Figs. 2.7a-e) and the results show that as the agpaitic coefficient increases:-

1, the modal volume percentage quartz slightly decreases.

Fig 2-6 Modal minerals v SiO_2

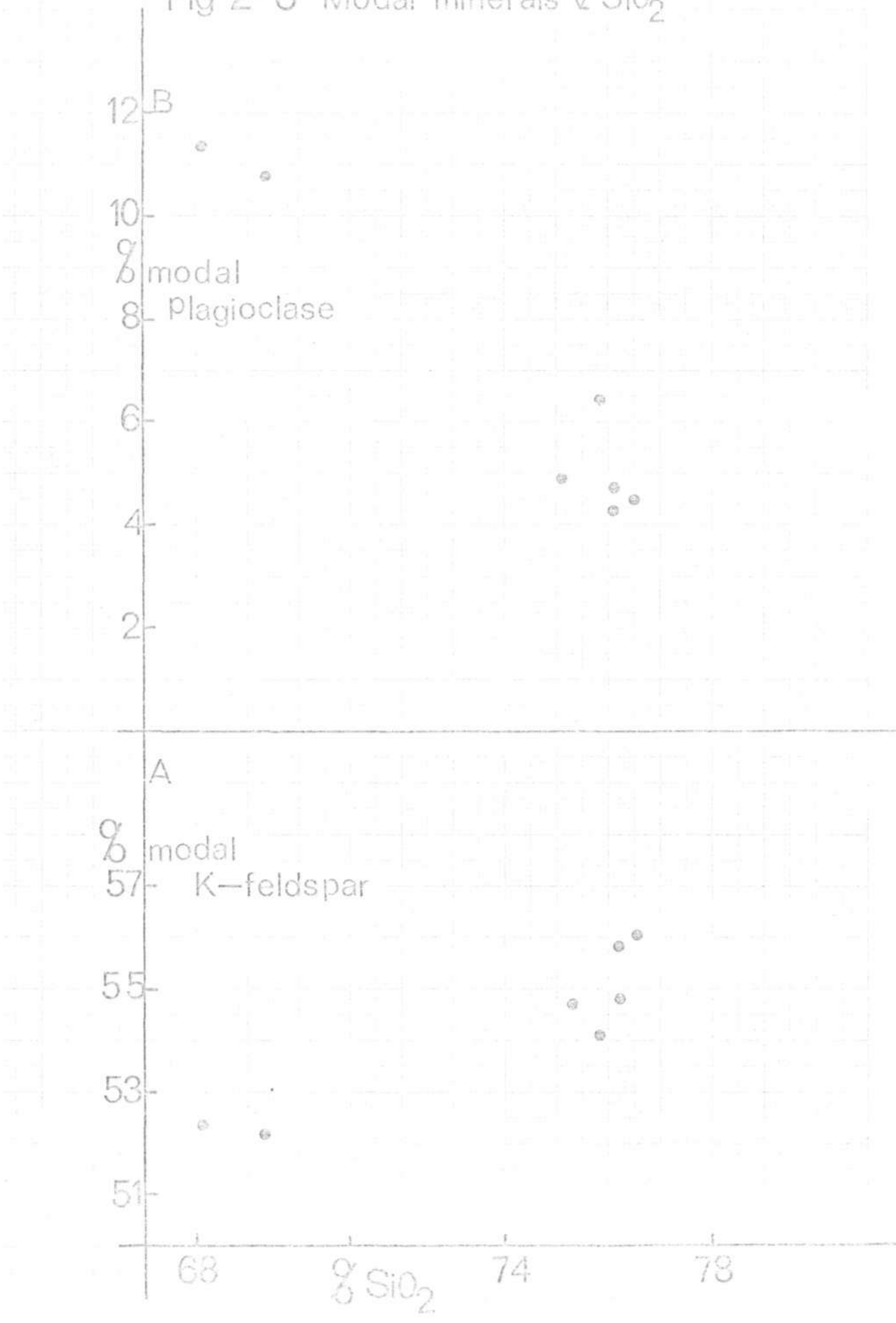
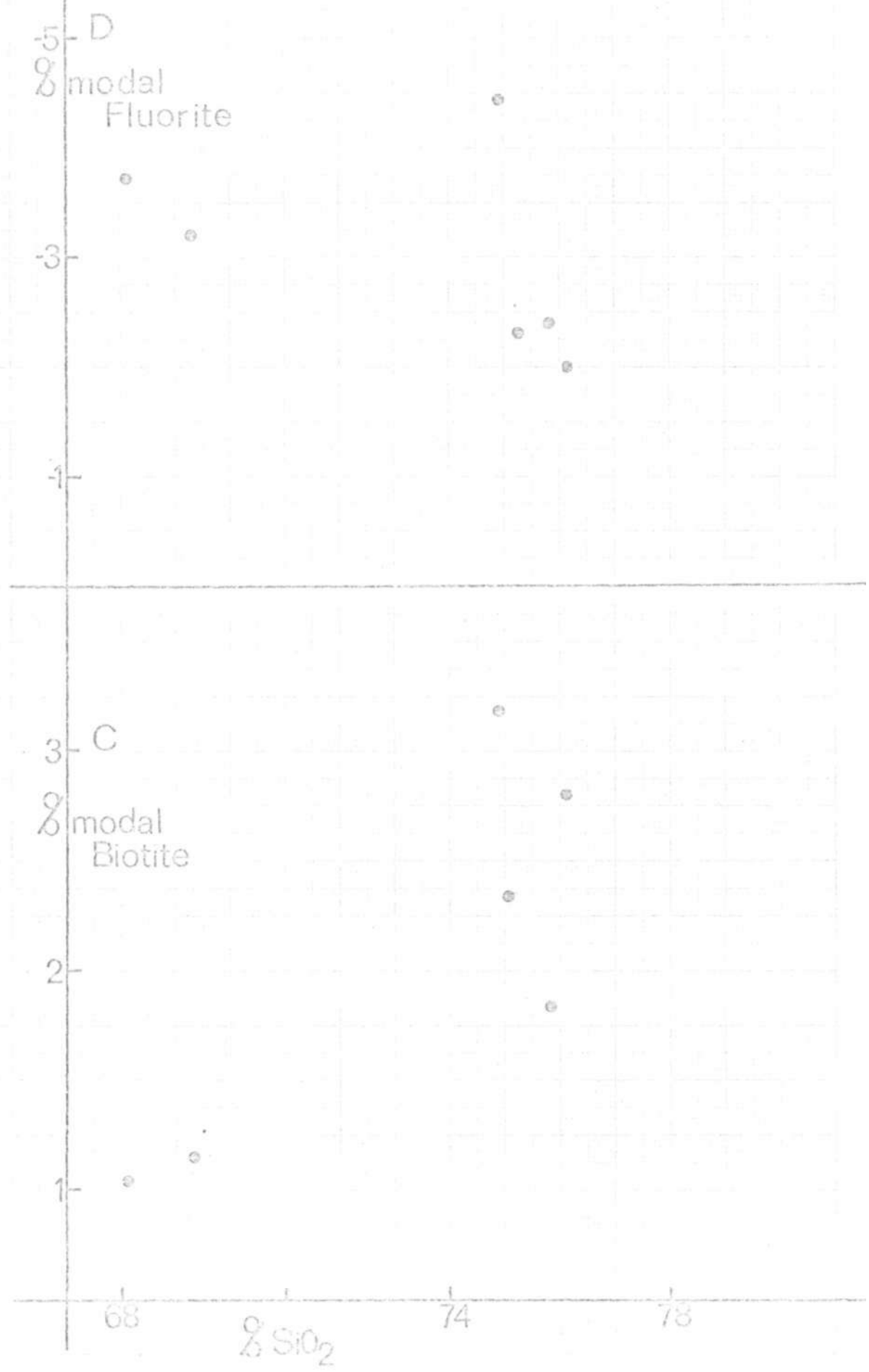


Fig 2–6 Modal minerals v. SiO_2



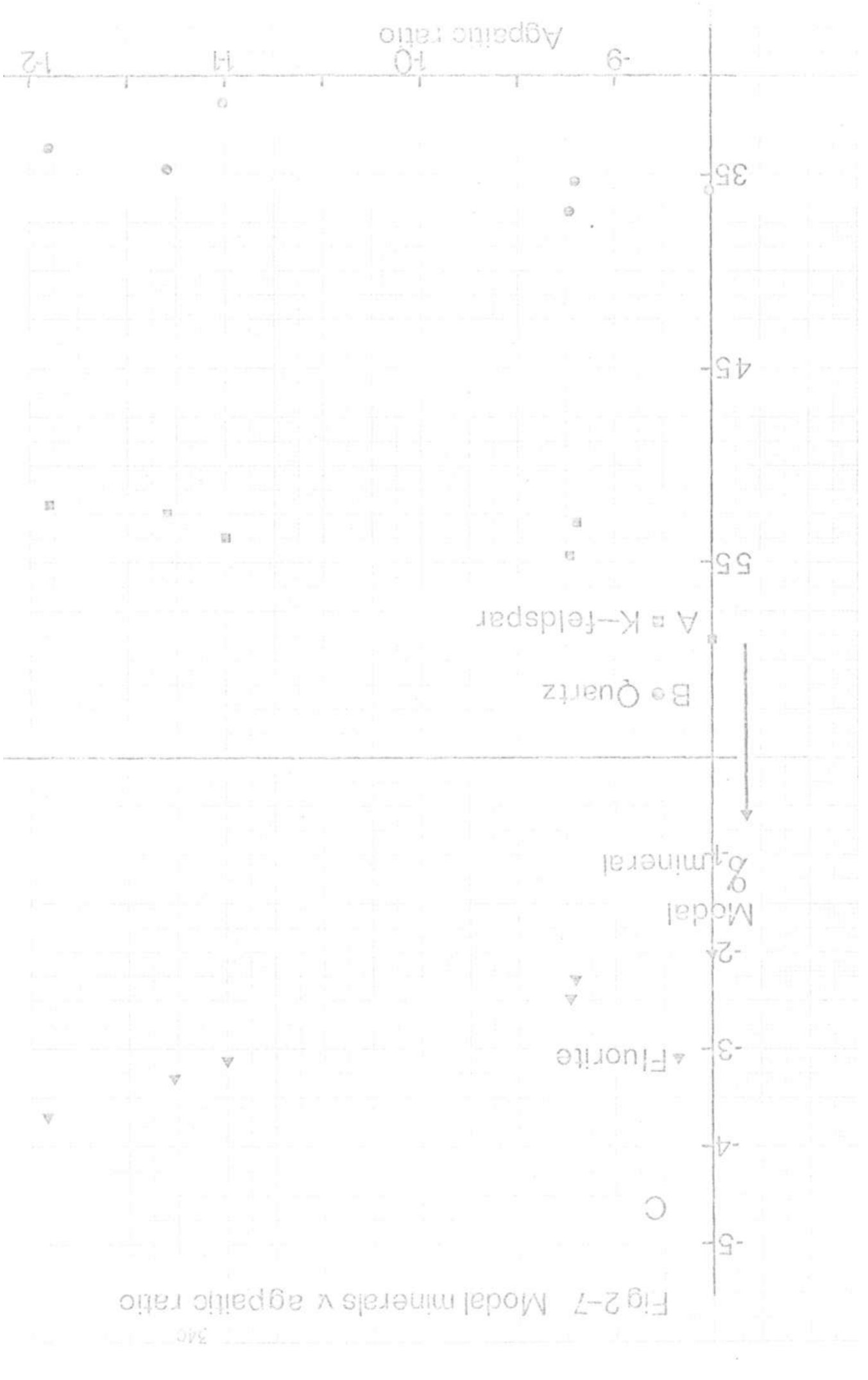
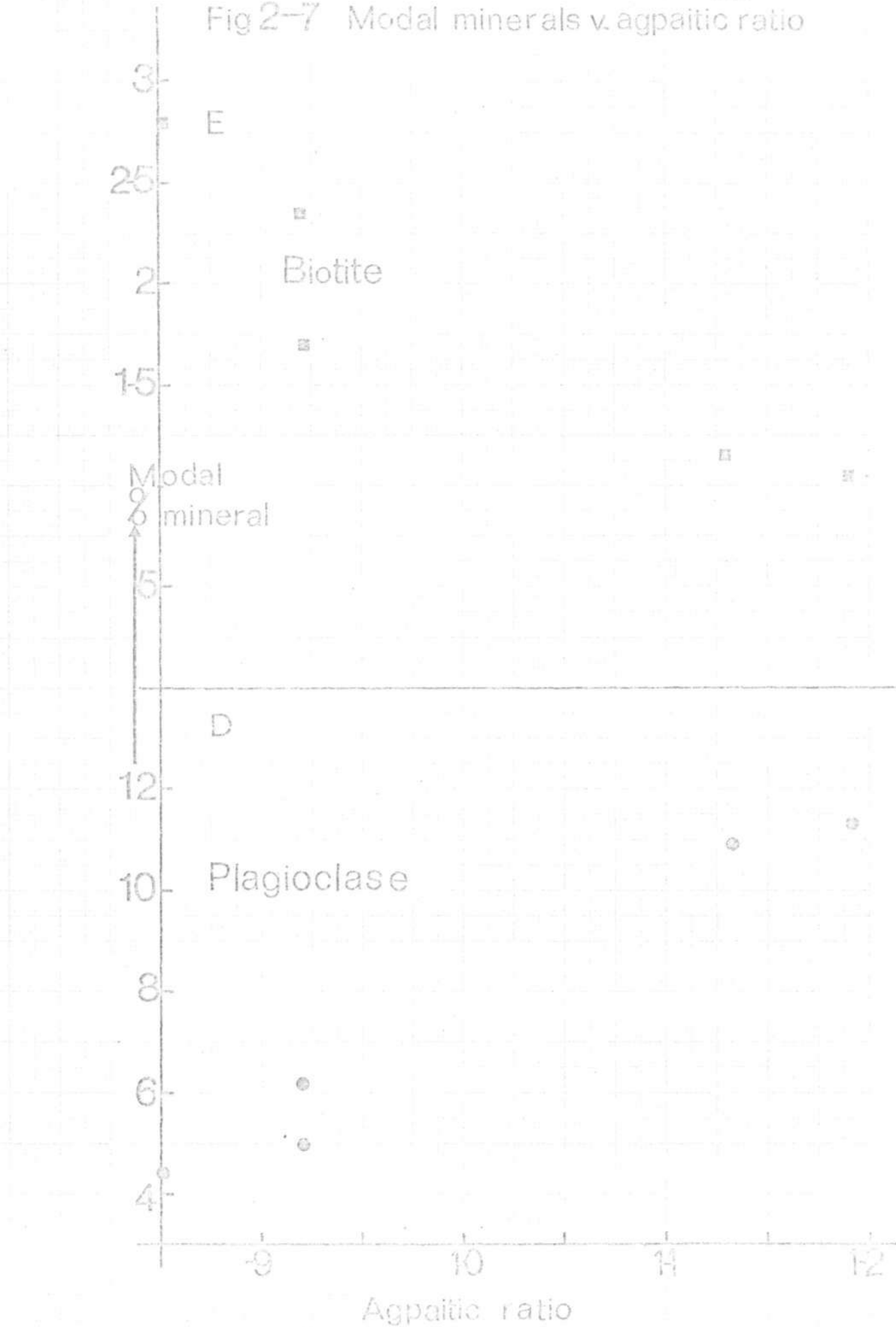


Fig 2–7 Modal minerals v agpaitic ratio

Fig 2–7 Modal minerals v. agpaitic ratio



2, the modal volume percentage orthoclase-microperthites decreases.

3, the modal volume percentage fluorite also increases.

4, the modal volume percentage albite increases.

5, the modal volume percentage biotite decreases.

The results of the analyses compare well with previously reported analyses of biotite granites from this granite province (Jacobson et al. 1958; Bowden and Turner, 1974; MacLeod et al., 1971 and Bowden et al. 1971). The high values of Na_2O in the two samples (LJ3-411 and LJ3-440) may be explained by the effects of albitisation associated with late hydrothermal action. This has been reflected in the mineralogy of the samples as well. In thin section the samples exhibit recrystallisation textures and quartz has been leached in them which is also reflected in the drop in silica as observed in the analyses. Albite has been introduced in the samples while the original perthites have been replaced by microcline. The agpaitic coefficients of the two samples indicate that they are peralkaline while the unaltered samples show plumasitic characteristics (agpaitic ratio 1).

The modal biotite also shows a decrease in the two samples which have this agpaitic tendency.

This is expected since the more agpaitic rocks of this province - the albite-riebeckitic-arfvedsonite granites usually have little or no biotite. The silica, iron and soda contents of these two samples are similar to the values found in the peralkaline granites as well as their agpaitic ratios. Perhaps the results of these samples compared with those of unaltered biotite granite reflect the effects of

late hydrothermal action which introduced dispersed mineralisation in both the plumasitic and agpaitic granites as well as albite and microcline.

Trace element chemistry

Some trace elements were analysed for in this same samples and the results are presented (Table 2.5). The distribution of the trace elements is relatively constant except in the two albitised samples, and the results from the normal biotite granite compare well with granites elsewhere. (Aleksiyev, 1970; Butler and Smith, 1962; Bowden and Turner, 1974, Bowden, Butler and Smith, 1962 and Bowden, Whitby and Van Breemen, 1975).

Rb concentrated well in the biotite granite with a range from 585-993 ppm, but this value drops to 15-36 ppm in the albitised samples. Sr shows a marked depletion and has a range from 0-5 ppm with a mean (12 samples) of 1.7 ppm. The albitised samples however have a range from 4-8 ppm and a mean (2 samples) of 6 ppm. Y is low in the two albitised samples with a range from 51-56 ppm and a mean of 53 ppm. In the normal biotite granite Y ranges from 109-147 ppm with a mean of 127 ppm. Zr content is similar in both the albitised and the unaltered granite and the value is similar even in the greisens (Table 2.6) with an average value of 286 ppm (17 samples). Cu is low in all the samples with a range from 0-8 ppm and a mean of 6 ppm (14 samples). Li concentrated well in the normal biotite granite but is depleted in the albitised samples. The Li content varies from 250 ppm-1482 ppm with a mean of 760 ppm (12 samples), but in the albitised granite the value drops to 32 ppm. The behaviour of Zn is similar to that of Li.

Table 2.3. Selected trace element analysis of Ririwai samples.

SAMPLE	Rb	Sr	Y	Zr	Li	Be	Cu	Pb	Zn	U	Th
L13-10	629	0	127	233	336	7	3	26	185	30	25
L13-26	585	0	109	68	250	7	7	42	185	nd	nd
L13-115	750	4	134	413	1482	5	8	56	828	80	72
L13-145	831	3	147	284	619	5	4	37	739	nd	nd
L13-150	797	2	113	277	473	3	7	105	396	nd	nd
L13-190	825	2	119	331	567	3	7	25	318	nd	nd
L13-205	993	4	144	343	761	7	5	15	398	53	51
L13-256	960	5	146	286	852	5	0	33	621	nd	nd
L13-290	727	0	127	279	511	6	6	25	374	nd	nd
L13-310	780	0	127	256	484	6	7	33	368	58	56
L13-315	689	0	129	602	585	7	3	15	380	nd	nd
L13-327	777	0	124	242	526	5	7	34	367	nd	nd
L13-411	36	8	51	285	30	6	7	25	164	81	73
L13-440	15	4	56	309	34	5	4	37	26	66	69

L13-10---L13-327 normal biotite granite Ririwai

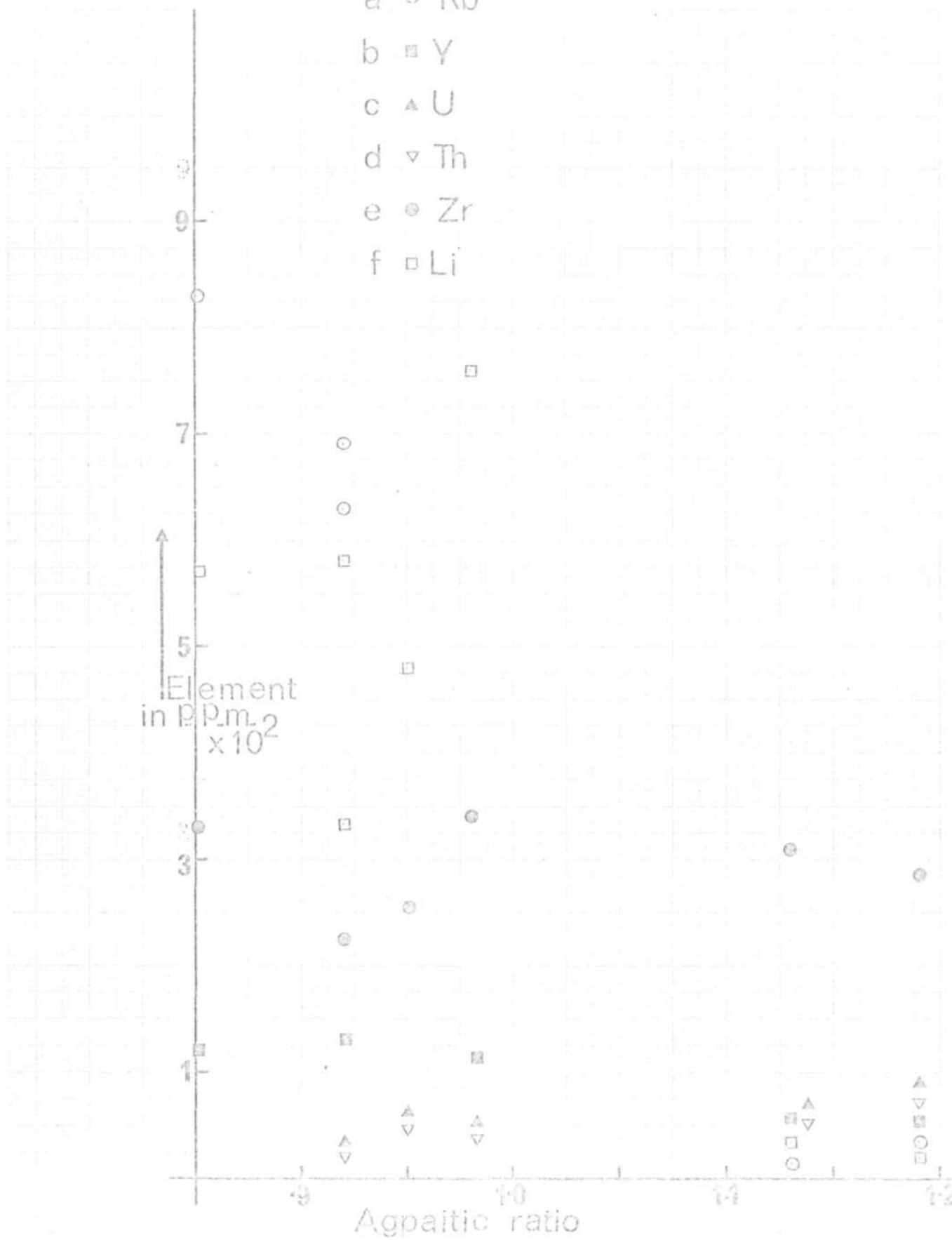
L13-411 and L13-440 albitised samples of the same biotite granite

Analysts: S.I. Abaa, R. Batchelor and E. Cox (1976).

The Zn values range from 185-828 ppm in unaltered granite, but in the albitised samples, it ranges from 26-164 ppm. Be concentrated similarly in both the albitised and unaltered samples with a range of 3-7 ppm. Pb is also similarly concentrated in the albitised and unaltered samples. Only six samples were analysed for U and Th and both elements tend to increase in the albitised samples.

A plot of some of the trace elements against the agpaitic ratios of the samples is given here (Figs. 2.8a-f). The most striking feature of the diagram is that the elements have clearly

Fig 2-8 Trace Elements v. Agpaitic ratio



fallen into two domains. In the first domain, the elements plot below agpaitic ratio of 1 and parallel to the elemental content axis, while in the second domain they plot above agpaitic ratio of 1.1 and are clustered together between the ratio 1.1-1.2 close to the agpaitic ratio axis. Mineralogically, the first domain is characterised by high modal biotite and orthoclase-microperthites and low modal albite while the second domain is characterised by very low modal biotite, low orthoclase-microperthites but high modal albite.

This albitization process causing chemical, mineralogical and elemental variation in the biotite granite has been recognised as being the effect of late hydrothermal fluids associated with mineralisation both in the biotite granites and the associated peralkaline granites. However the actual situation may not be so simple as seen from these samples. The samples of the albitised zone are only two, but their mineralogy and chemistry which is different from the altered wall rock of the main lode at Ririwai confirm the view that there are two stages of alteration and mineralisation in the biotite granites (Bowden; 1975).

Bowden stated that as the biotite granites consolidated, late-magmatic autometamorphic changes were induced by rising silicate fluids, converting the normal biotite granite into a plumasitic apogranite with columbite, thorite and xenotime. Perhaps this may be the alteration and mineralisation stage manifested in the two samples (L13-411 and L13-440). The mineralisation in lodes and veins at Ririwai is therefore associated with his (Bowden's) second alteration and mineralisation. In this second mineralisation stage, lower temperature post-magmatic metasomatic greisenization by aqueous

fluids subsequently introduced cassiterite with sulphides as subvertical and horizontal veins along cooling joints, fissures and ring fractures.

2.3. Chemical and mineralogical changes associated with wall-rock Alteration.

The physical features of wall-rock alteration most prominent at Ririwai are the colour changes observed in the reddened granite and darkened greisens, while textural variation is prominent in the greisens. In order to determine the chemical and mineralogical changes involved in the wall-rock alteration, samples of the greisen and reddened granite were studied in thin section, and one sample each of the reddened granite, greisenised granite and greisen were analysed for major and some trace elements (Table 2.6). Similarly, a modal analysis was carried out on the reddened granite and greisenised granite (Table 2.7). These results are in turn compared with one sample of unaltered biotite granite close to the surface (L13-10). In Table 2.6 the letters X, Y and Z represent the gains or losses in reddened granite, greisenised granite and greisen respectively. Similarly in Table 2.7 X and Y represent the gains or losses in modal minerals in reddened granite and greisenised granite respectively.

In case of the reddened granite, there is a slight decrease in the silica content, alumina, titania, ferric iron and lime, but a marked decrease in soda. There is also a slight increase in ferrous iron magnesia, fluorine, chlorine and absorbed water but a remarkable increase in potash. All the trace elements analysed for, namely Sn, Cu, Zn, Pb and Li show an increase. The marked increase in potash and the decrease in soda is confirmed by the mineralogical evidence in

Table 2.6. Chemical analysis of Altered Wall-Rock.

	L13-10	RS 1	RS 2	RS 3	X	Y	Z
SiO_2	75.23	74.92	78.27	80.63	- 0.31	+ 3.34	+ 5.40
Al_2O_3	12.80	11.35	10.33	6.57	- 1.45	- 2.47	- 6.23
TiO_2	0.08	0.07	0.05	0.06	- 0.01	- 0.03	- 0.02
Fe_2O_3	0.42	0.41	0.38	0.54	- 0.01	- 0.04	+ 0.12
FeO	1.15	1.84	4.36	5.14	+ 0.19	+ 3.21	+ 3.99
MnO	0.04	0.03	0.11	0.15	- 0.01	+ 0.07	+ 0.11
MgO	0.09	0.12	0.14	0.10	+ 0.03	+ 0.05	+ 0.01
CaO	0.48	0.38	0.12	0.39	- 0.10	- 0.36	- 0.09
Na_2O	4.14	0.44	0.23	trace	- 3.17	- 3.91	- 4.14
K_2O	4.62	9.88	1.46	0.28	+ 5.26	- 3.16	- 4.34
P_2O_5	0.05	trace	nil	trace	- 0.05	- 0.05	- 0.05
F	0.32	0.46	1.48	1.94	+ 0.14	+ 1.16	+ 1.62
Cl	0.01	0.02	trace	0.03	+ 0.01	+ 0.01	+ 0.02
H_2O^+	0.39	0.27	0.56	0.69	- 0.12	+ 0.17	+ 0.30
H_2O^-	0.07	0.19	0.12	0.04	+ 0.12	+ 0.05	- 0.03
	99.89	99.88	97.61	96.53			
Less O	0.17	0.21	0.63	0.78			
Totals	99.72	99.67	96.98	95.75			
Sn	16	1750	6607	24860	+ 1734	+ 6591	+ 24844
Cu	3	786	4776	6027	+ 783	+ 773	+ 6024
Zn	185	1800	14700	21300	+ 1615	+14515	+ 21115
Pb	26	2700	16740	14400	+ 2674	+16714	+ 14374
Zr	233	310	186	230	+ 77	- 47	- 3
Li	336	1050	2950	2997	+ 714	+ 2614	+ 2661

L13-10 unaltered granite at depth of 10m.

RS 1 Reddened granite, surface

RS 2 Greisenised granite surface.

RS 3 Greisen from blasted lode zone.

X, Y and Z are gains and losses in the reddened granite, greisenised granite and greisen respectively.

Analysts: S.I. Abaa; R. Batchelor (1976).

which the sodic feldspar of the original granite has been replaced by a non-perthitic potash feldspar. This is also confirmed from the modal analysis, in which there is 100 per cent decrease in the modal albite and about 8 per cent increase in the modal potash feldspar. The increase in magnesia, ferrous iron-fluorine and lithia can be attributed to the development of a green mica, formation of sericite and chlorite and other alteration products. The rise in Pb, Cu, Sn, and Zn has been accounted for by the presence of galena, sphalerite and sometimes cassiterite. In thin section, it is common to observe grains of sphalerite and cassiterite in the reddened granite.

Greisenised Granite.

The greisenised granite shows a marked increase in ferrous, silica and fluorine but smaller increases in manganese, magnesia, chlorine and absorbed water. Small decreases are observed in titania and ferric iron, while remarkable decreases occur in

Table 2.7. Modal analysis of altered wall-rock.

	L13-10	RS 1	RS 2	X	Y
Quartz	35.5	31.0	42.6	- 4.5	+ 7.1
Orthoclase-perthite	54.7	62.9	14.9	+ 8.2	-39.9
Albite	4.9	trace	-	- 4.9	- 4.9
Mica	2.3	3.8	16.5	+ 1.5	+14.1
Fe oxides	0.1	4.3	0.8	+ 4.2	+ 0.7
Fluorite	0.2	0.4	1.6	+ 0.2	+ 1.4

L13-10; Unaltered biotite granite (from Table 2.6)
RS_1; Reddened granite
RS_2; Greisenised granite.
X; Gains and losses in reddened granite.
Y; Gains and losses in greisenised granite.

alumina, potash soda and lime. Furthermore the trace elements Cu, Pb, Zn, Sn, and Li show remarkable increases. The increases in fluorine, lithia and magnesia and iron are due to the extensive

development of micas which is further indicated by large increase of 14 per cent in modal mica. The decrease in ferric iron is due to the elimination of much of the haematite developed earlier. The impoverishment in soda, potash and lime are all due to the replacement of the original feldspars by quartz, mica and some ores. The increase in silica has been reflected in the increase in modal quartz. Similar increases have been observed in the modal percentage of fluorite. Fluorine increase in the greisen can therefore be attributed partly to the formation of fluorite as well as micas. The large increases in Sn, Cu, Zn and Pb have been accounted for by the occurrence of massive ores as cassiterite, sphalerite, galena and chalcopyrite.

Greisen In the greisen remarkable increases occur in silica, ferrous and ferric iron, fluorine, lattice water and manganese. Large decreases occur in alumina, soda and potash. The large increase in silica is due to the formation of quartz while fluorine is accounted for by fluorite and mica. Lithia is accounted for by mica while manganese is mainly accounted for by the introduction of wolfram in the small ore bearing veinlets in the greisen. The increases in total iron (FeO and Fe_2O_3) can be accounted for by the iron rich micas, and by the formation of some pyrite and chalcopyrite. Most of these minerals partly formed at the expense of the feldspars of the original granite which have been eliminated in the greisen, thus the large decreases in the soda, potash and alumina content. The increases in Sn, Cu, Zn and Pb are due to the development of cassiterite, chalcopyrite, sphalerite and galena.

The potash enrichment of the reddened granite zone may have come from the potash released from the greisen zone as well as some potash introduced by ore fluids. The consistent association

of the greisen and reddened granite zone indicates that the potash was transferred from the greisen zone into the adjacent part altered granite and this potash enrichment of the reddened granite zone must have taken place contemporaneously with the greisenisation of the adjacent zone. The greisenised granite in which some reddened potash feldspar still occurs possibly represents a progressive transition and greisenisation advance into the surrounding wall-rock. However there is a clear distinction of the two zones, except for occasional smears and clots of green mica in the reddened granite. The wall-rock alteration can be ascribed to two main distinctive alteration processes; greisenisation of the original granite resulting in the formation of a mica-quartz rock and haematization of the original granite (Wilson; 1972) producing the reddened granite, also associated with disseminated ore minerals. Other observed processes include kaolinization, chloritisation, sericitization and silicification.

The analyses (Table 2.6 and 2.7) have shown that the alteration of the biotite granite at Ririwai involved an increase in silica, lithia, fluorine, ferrous iron, pb, Cu, Zn, Sn lime and magnesia while potash initially increased but decreased together with soda in the final product of the alteration. Changes in some of the other elements are very small and could not be very significant. Perhaps the most important chemical process of the wall-rock alteration here is hydrogen metasomatism, in which hydrogen ions are added to the rock and the base metal cations are released. Some of the chemical reactions thought to have taken place are those of simple hydrogen metasomatism of the silicates and are presented here (Hemley and Jones, 1964; Meyer and Hemley, 1967; Park and McDiarmid; 1970).

Here only very simplified forms of the equations are

presented and lithium mica has been substituted in one of the equations since micas are abundant in the altered rocks as compared to chlorite and sericite. Some of the reactions may have taken place simultaneously and over a period of time.

(1) Replacement or conversion of plagioclase.

$$\text{Plagioclase} + 2H^+ + K^+ \text{ ------ Sericite} + Na^+ + Ca^{2+} + 3\ SiO_2 \text{ (quartz?)}.$$

(2) Kaolinisation of plagioclase.

$$\text{plagioclase} + 4H^+ + 2H_2O \text{ ---- kaolinite} + 4\ SiO_2 + 2\ Na^+ + 2\ Ca^{2+}$$

(3) Replacement of K-feldspar by chlorite and quartz.

$$\text{Orthoclase} + 4H^+ + 2H_2O \text{ ----- chlorite} + 2K^+ + 6SiO_2 \text{ (quartz)}.$$

(4) Replacement of K-feldspar by mica and quartz

$$\text{Orthoclase} + 4H^+ + 2H_2O \text{ ----- ?Li-mica} + 2K^+ + 6\ SiO_2.$$

(5) Replacement of biotite by Li-mica.

$$\text{Biotite} + 4H^+ \text{ ----- ?Li-mica} + (Mg\ Fe)^{2+} + 2K^+ + 3SiO_2.$$

In equations 1 and 2, the released Na^+ may have gone into the lattices of other minerals, while Ca^{2+} may have contributed to the formation of fluorite. In equation 5 the Mg and Fe may all have been used up in the formation of micas while some of the Fe may have been used up in the formation of wolfram with manganese as well as other minerals like pyrite and chalcopyrite. The released SiO_2 may have remained either as quartz or as silica combined with the micas. The released K^+ may have been taken up by the micas as well since an analysis of a mica from the greisen shows 8.84 per cent K_2O (Table 2.3).

2.4. Mineralisation

Several ore minerals are concentrated in the main lode, veins, disseminated in the altered wall-rock and are present in the alluvials. The distribution of the ores along the lode is however irregular both along the strike and at depth. Drill cores studied have not given much information about the attitude of the lode and ores at depth. However other drill cores show that the lode continues downwards to depths of more than 500 m and the ores are still randomly distributed at depth. In the eastern section of the lode, cassiterite is more abundant, followed by sphalerite and some wolfram. In the western end of the lode, the predominating ores are galena, sphalerite and chalcopyrite, while wolfram is found in the adjacent vein system, where Haag (1943) stated that the ratio of wolfram to cassiterite is about 4:1. However the mineralisation is associated with the following ores minerals:- Copper pyrites, iron sulphides, galena, columbite, zinc blende, wolfram, cassiterite, molybdenite, and replacement minerals of the above ores.

Cassiterite

Cassiterite veins are genetically related to the biotite granite. Besides occurring in the main lode, it also occurs in the numerous smaller veins which are spread through the biotite granite.

Some short veins containing cassiterite extend into the rhyolites on the eastern edge of the biotite granite, but do not contain significant economic ores. The cassiterite occurs as coarse and fine disseminations in the greisenised granite and greisens. The distribution of cassiterite in the quartz veins is irregular, usually with zones of rich ore

separated by massive barren quartz. In the greisens, fine well twinned euhedral crystals can be observed particularly in the small vugs containing some clay-like mineral (? adularia). The cassiterite is either black, reddish or yellowish to grey. In thin section, the greisen cassiterite varies from brownish to reddish and yellowish with individual masses showing zonal growth of varying colours. The cassiterite is pleochroic from pale yellow to deep red and does not usually go into complete extinction. The pleochroism may be due to the presence of tantalum and niobium. It has been shown that the Ririwai cassiterite is magnetic and can be demagnetised by heat treatment (MacLeod and Jones; 1955).

Wolfram

Wolfram is found only in the veins closely associated with bands of coarsely crystalline quartz (Haag; 1943) and sometimes pseudomorphs of limonite after wolfram, and solution cavities filled with powderly tungstite can be observed in weathered veins. The wolfram is found associated with comb-like structures in quartz, and the crystals are usually brown or black. It may be found associated with secondary feldspars (? adularia) in cavities, probably deposited from hot fluids.

Columbite Columbite is found disseminated in the biotite granite and can be obtained from the decomposed rock. It is possible that columbite could be in the altered wall-rock as well.

Galena and Sphalerite are abundant in the vein quartz particularly in the central quartz of the main lode. They form massive ores and occur irregularly, usually interrupted by large zones of barren quartz. Other sulphide ores present, both in the main lode and the adjacent veins include

pyrite and chalcopyrite. The sulphides may be observed as impregnations in the greisens. At the western end of the lode, it is common to observe some azurite and malachite in the lode rubble. The two minerals may be secondary due to hydration and chalcopyrite could alter to malachite.

Alluvial deposits

In the past, the greater part of tin mining at Ririwai has been in the alluvials. But presently, the Gold and Base mining company is drilling in the hard rock and it is hoped that production may soon start. Much tin had been won from shallow alluvial deposits overlying the biotite granite, and along the streams and gullies that drain the central biotite granite. Rich alluvial deposits have been obtained up to 20 m depth of the central biotite granite overburden, while shallow alluvials for several kilometres downstream have yielded economic tin deposits. Cassiterite occurs in this area in form of alluvials, gravels and as detritals (Thomas et al; 1922). The alluvial cassiterite is usually black with occasional pale yellow varieties. The Nigerian tinstone has been described as black to ruby or pale yellow, and assays of about 75 per cent metallic tin are common (Falconer; 1922). The cassiterite crystals are usually euhedral, and different localities may exhibit different forms of cassiterite. Cassiterite associated with pegmatites from Ilorin province has rounded edges while some crystals exhibit distinct mould impressions (Whitehead; 1972). At Ririwai, cassiterite may also be found as eluvial deposits in form of coarse crystalline tinstone along the weathered cassiterite bearing veins.

Columbite is only in the alluvials and may be more abundant than cassiterite in some localities. Wolfram has been found

only in lodes and to a smaller extent as eluvial deposits. It has been explained that wolfram rapidly decomposes and disintegrates once it has been released from the lode and veins (Haag; 1943).

Thorite Monazite and Zircon (as malacon)

Both thorite, monazite and malacon are found in the alluvials and are believed to have been concentrated as a result of decomposition of the biotite granite. However their economic extent has not been well investigated.

Alluvial deposits have been largely worked out but the prospects for hard rock mining are great as the Gold and Base Mining Company is developing a mine. It is hoped that large production of not only cassiterite but also galena, sphalerite and possibly chalcopyrite may be feasible.

Origin of the Ore mineralisation

Mineralisation in the Ririwai complex is restricted in the biotite granite with minor extensions into the surrounding rhyolites. However some form of mineralisation occurs in the albite-riebeckitic-arfvedsonite granite mainly with pyrochlore. Mineralisation is associated with pegmatitic knots and patches, but such form of mineralisation is minor and usually exhibited only at contact margins of the associated rocks. Such mineralisation is irregular with subspherical clots and may occur as typical drusy cavities, with the contained crystals growing from the walls of the cavity towards the centre. Elsewhere in this province, such occurrence of mineralisation has been reported (Raeuburn, Bain and Russ; 1927). In some places the knots may have no central cavity, but may consist of an aggregate of coarse crystals of quartz and feldspar with or without wolfram. The mineralisation in the biotite granite is believed to have been in two stages;

dispersed mineralisation and post granite mineralisation which occurs as lodes veins and stringers.

The generation of an ore deposit requires several favourable combinations of circumstances. The metals of the ores must have an origin and the source rocks supply the metals of such ores, which under adequate physical and chemical conditions may concentrate in a fluid phase. The fluid may then migrate to another environment where some other physical and chemical conditions may be appropriate for total or selective deposition. In some cases only physical or chemical changes may be required for such deposition, or even only interaction with meteoric water. In other environments, a necessary constituent such as sulphides may be required from another fluid or by inorganic or bacterial reduction of sulphates (White; 1974). Perhaps the most important factors controlling metal transport and deposition include temperature pressure and other chemical characteristics such as salinity, pH of fluids and fugacities of oxygen and carbon-dioxide. Other factors are also important, such as the proportions of metal ions and sulphide species (Rye and Ohmoto; 1974). After the metals have concentrated in the fluids, which may either be of magmatic origin or meteoric and connate water, then migration would start provided there are channelways, or the containing rocks provide the required porosity. The migrating fluids may require some driving force, and in hydrothermal systems such as Ririwai, magmatic heat may be the energy essential for this. In case of fluids escaping from sediments, localised heating may result in thermal expansion of pore liquid, promoting convection and deep circulation of meteoric water, while in sediments under-

going compaction with fluids escaping during progressive metamorphism, gravity may be the dominant factor (Helgeson, 1968; White; 1968).

Fluids of hydrothermal deposits

The constituents of fluids of hydrothermal deposits obviously include magmatic water and the associated anions and cations may also be of magmatic origin, or may be picked up at various stages of migration. The ions in the fluids may include Cl^-, Br^-, F^-, S^{2-} $H,^+$ O^{2-} and N^{2+} (Berth et al. 1973; Robinson; 1974). Other ions include Si^{4+}, C^{4+} Mg^+, Na^+, K^+, Ca^{2+}, Fe^{2+} and Fe^{3+} (White and Waring; 1963, Krauskopf; 1967). Some metal ions such as Pb^{2+}, Cu^{2+}, Zn^{2+}, Sn^{4+} and Mo^{4+} may also be present depending on the environment (Doe and Stacey, 1974; Heyl et al. 1974). Such may be the composition of a hydrothermal fluid. As the fluid migrates, chemical reactions between the component phases as well as with the wall-rock take place. Changes in pressure, temperature, distribution coefficients, acid/base strengths, gas fugacities, pH of fluids and even changes in the oxidation states of the ions may cause deposition along the migration paths If such depositions are large then ore bodies are formed.

At Ririwai, the tin and sulphide lode and veins are intimately associated with the biotite granite and is due to post-granite alteration, hydrothermal and pneumatolytic actions. Columbite was deposited at an earlier stage during the consolidation of the biotite granite. Cassiterite, wolfram and sulphides were deposited in fissures as the biotite granite was cooling.

Ore fluids had concentrated in the residual aqueous fluids at deeper levels and after the lode fractures were

formed, the ore fluids at depth were released. The fluids released then ascended the fissures and deposited ores as well as causing intense alteration of the wall-rocks. As can be seen from the mineralogy of the lode, veins, greisens and reddened granite, the ore fluids may have contained iron, fluorine, tin, chlorine, lithium, oxygen, carbondioxide, sulphur, water, lead, zinc and copper. Other contents of the ore fluids were Mn^{2+}, Na^{+}, K^{+}, Mg^{2+}, Si^{4+}, P^{5+} Mo^{4+} W^{4+}, Ca^{2+} Al^{3+} Fe^{2+} Fe^{3+} and possibly As^{2+}. It is possible that greisenisation at depth also released potash to further concentrate the ascending fluids. The fluids, as they rose deposited some of their contents as quartz and wolfram. If sulphur had not been in the original fluids, then cations like Cu^{2+} Zn^{2+} and Pb^{2+} in the fluids would react with sulphur from the surrounding cooling granite, thus precipitating their sulphide ores. However at Ririwai sulphide reactions must have been between metal ions and sulphur of the fluids since the host granite contains little or no sulphur.

As the mineralisation at Ririwai is of the cassiterite-wolfram-quartz type, the fluids may have been very rich in K^{+} and highly concentrated with CO_2, P_2O, W, Cu, Zn, Mn, Pb and possibly fluorine (Barabanov; 1965). The fluids were initially neutral or weak alkaline and their high potash content must have been released to the wall-rocks as can be seen in the reddened granite, where all the soda has been leached and there is a large increase in potash. Cassiterite may have been in the fluids either in form of alkali-stannate (Simmons, 1930a; 1932b) or as alkali-thio-stannate (Smith; 1947). On the other hand, the increase of fluorine in the greisens over the original granite indicates that cassiterite

may have been transported in the form of hydroxofluor-stannate complex of tin of the $[SnFx(OH)_{6-x}]$ type (Barsukov, Kuril'chikova; 1966). Barsukov and Kuril'chikova (1966) found by determination of fluorine content in the gas-liquid inclusions in vein quartz from sulphide-cassiterite deposits that the hydrothermal solutions represented by these inclusions contained more than enough fluorine to transport tin. They concluded that hydrothermal solutions, both of the quartz-cassiterite and sulphide cassiterite deposits transport tin in form of hydroxo-fluo-stannate complexes. However it is the writer's opinion that both complexes of alkali-stannate and hydroxo-fluo-stannate were responsible for transport of tin at Ririwai.

If cassiterite here was transported in the fluids in this form, then it would have been deposited as the silica content of the fluid increased and the fluid became more acidic. This deposition would have been aided by a temperature gradient, and as fluids migrated in alkaline solutions as hydrated complexes, deposition and crystallisation was the result of decomposition or hydrolysis of the stable alkali forms in increasing silica acid conditions of the fluids (Ganeyev; 1973). The deposition of cassiterite took place at the same time as the ores of Cu, Zn, Pb, Mo wolfram and quartz at the centre of the veins fissures. The presence of galena and sphalerite in the greisens may be due to migration as well as replacement processes (Park and McDiarmid; 1970) and this may be the cause of the swellings of the greisens in some places. The formation of pale green mica and a whitish clay-like feldspar (?adularia) in the greisens could be from the amounts of potash, lithia, ferrous and ferric iron and fluorine carried in the pneumatolytic phase, or from the

larger amounts carried in solutions that deposited the quartz veins, tin, tungsten, lead, zinc, copper and other ores.

The fissures in the biotite granite were open and were filling with quartz and ores since zones of quartz and ore occur in some veins surrounding a more centrally formed quartz with crystals growing inwards from the initially formed vein material. The initial pneumatolytic phase that ascended started greisenisation before deposition commenced by hydrothermal fluids. It has been suggested that in post-magmatic ore formation, hydrothermal and pneumatolytic phases coexist in time and space (Ovchinnikov; 1965). At Ririwai, in the early pneumatolytic stage the ore fluids were probably rich in fluorine, but at a later stage, the fissures were filled with siliceous solutions from which the vein quartz was deposited. It was at the early stage that fluorine was deposited in the greisens along with the early fluids that started the wall-rock alteration. This pneumatolytic stage was associated with and closely followed by the rise of siliceous liquids and water solutions (Smith, 1954; Ganeyev; 1974) with dissolved salts from which the lode and veins were formed.

The telescoping of the ores is either due to the overlapping of deposits from two or more magmatic centres, or by repeated periods of mineralisation (Park and McDiarmid; 1970).

Telescoping is said to be restricted largely to deposits formed under shallow conditions where changes in temperature and pressure are rapid. Where conditions change gradually, as in the high-temperature high-pressure deposits,

zoning is generally present and is expressed at least by variation in fineness, for example, of gold (Pryor; 1923), or in the amount of minor constituents. This shows that mineralisation at Ririwai may have taken place under shallow conditions and the deposition of ores occurred at relatively low temperatures since the ores exhibit no zoning and some of the veins occur with little or no wall-rock alteration. However it has been suggested that most hydrothermal tin deposition occurs in the temperature range 300-500°C (Little; 1960) while Hesp and Rigby (1971) stated that the transport of tin by hydrothermal solutions at low temperatures lower than 300°C as sodium stannate is possible. It seems likely that deposition at Ririwai may have occurred between 300-600°C owing to the shallow depth of deposition.

Pegmatites are absent, except for a few knots and streaks in the marginal facies of the Ririwai mineralised granite. This may be due to the difference in temperature between the consolidating granite, the ore fluids and the country rocks. This would produce a semi-chilled effect, giving rise to the pegmatitic knots and patches at the margins of the granite. Ore fluids did not escape from the residual concentrates until the lode and vein fissures had formed. The confining pressures were then released (?suddenly) after the fracturing of the granite massif, and this led to boiling off of the ore fluids. The release of gas was followed by solutions rich in silica and water (Smith; 1954) which eventually filled the lode channels.

The biotite granites of Nigerian tin field have two related periods of primary mineralisation. A prejoint auto-metamorphic mineralisation in which Nb, Th, Be, Zr and Hf were dispersed during the consolidation of the biotite granites.

The second period was a post-joint replacement mineralisation in which Zn, Sn, Pb, Cu, Mo, and Bi were introduced into crystalline host rocks along cooling joints, fissures and ring fractures (Bowden and Jones; 1975). Both related periods of mineralisation occur in the biotite granite at Rariwai as shown by this study. Bowden and Jones concluded that such processes must be related to the end stages of magmatic crystallisation and the development of residual fluids. In this study the occurrence of columbite, thorite, monazite and malacon as dispersed minerals has been found and cassiterite, sulphides and other ores correspond well as introduced into the crystalline biotite granite, along cooling joints, fissures and ring fractures, at a later stage than the dispersed form.

CHAPTER 3

GINDI AKWATI

General Description

The Gindi Akwati lode is a small zone of mineralisation in Basement Older Granite close to the contacts between the older granite and a granite porphyry dyke. The area mapped for this study is located as a point on Longitude $8^{o}50'E$ and Latitude $9^{o}27'N$. The area trends approximately N-S and is about 100 m wide and 800 m long (Fig. 3.1).

The area occurs in the Rop Complex, in the central region of the Jos Plateau where the Younger Granites occupy an area of about 256 km^2. The Rop Complex generally contains a series of dyke rocks and a central prominent Younger Granite massif. Although the Rop Complex encloses a large area of Basement rocks, the Younger Granite rock types found in other ring complexes of this province are also found here. Both volcanic and plutonic cycles of magmatism form the complex. Rhyolites, explosion breccias and quartz porphyries are the volcanic group of rocks.

The granitic cycle, initiated by granite porphyries was followed by a succession of biotite and riebeckitic-arfvedsonite-granites, the cycle being concluded by late granite porphyries and a swarm of late dolerite dykes. Other prominent massifs are the Older Basalts mainly decomposed to clay material but still forming high flat topped hills. These Fluvio-Volcanics are usually capped with laterite, while sands and gravels occur beneath the decomposed basalts.

The Gindi Akwati lode occurs on the western edge of the Rop Complex (Fig. 3.2). The rock types in the vicinity are, a granite porphyry dyke, swarms of narrow late dolerite dykes,

Figure 3.1 is the geological map of the Gindi Akwati mineralised zone. The greisen and mylonitised zones are the main ore bearing zones. The first part of the map is the northern portion of the area, and the lower portion is on the second map on which the explanation is given.

Scale. 1 cm = 20 m.

FIG. 3.1

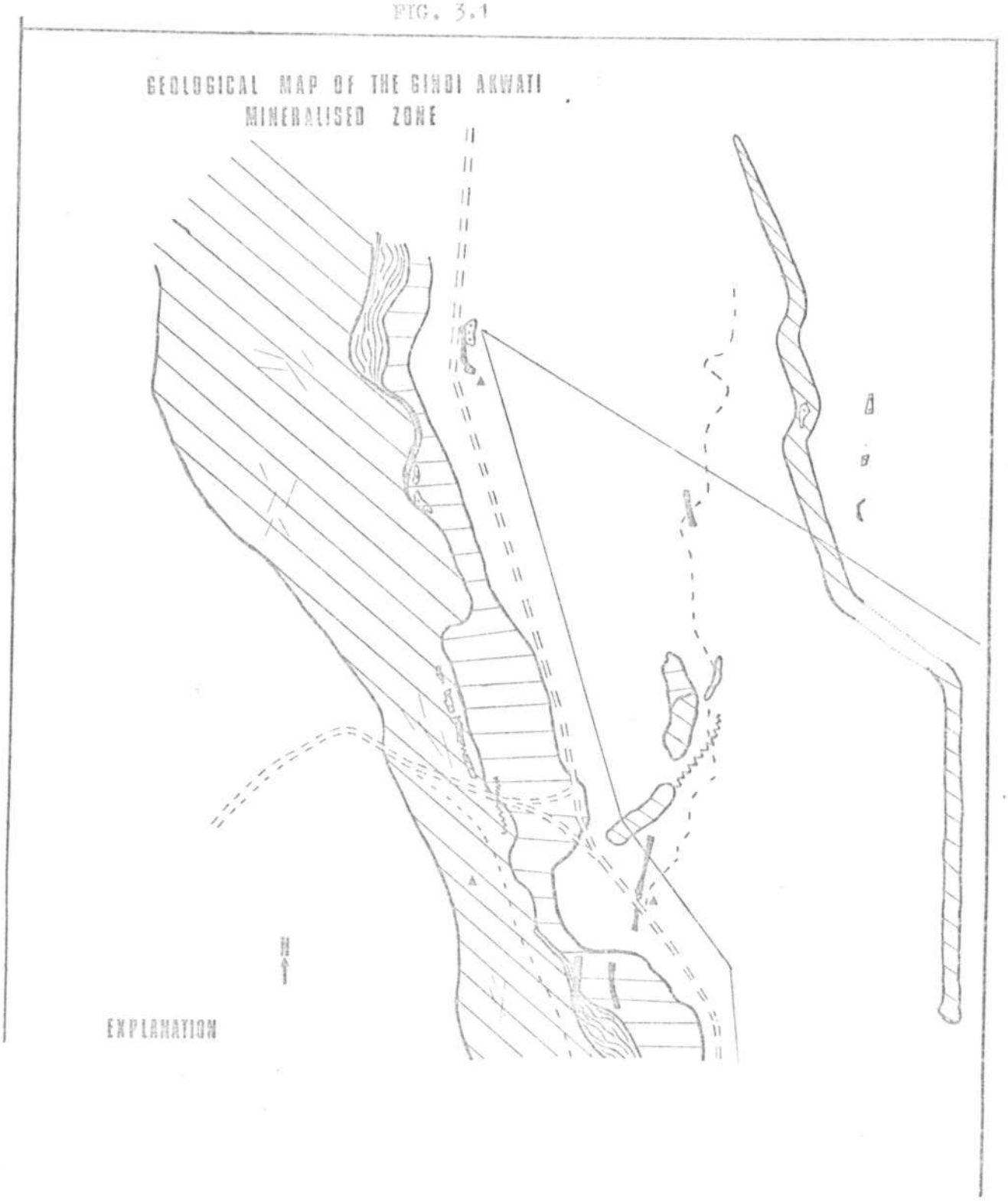

GEOLOGICAL MAP OF THE GINDI AKWATI
MINERALISED ZONE
EXPLANATION

FIG.3.1

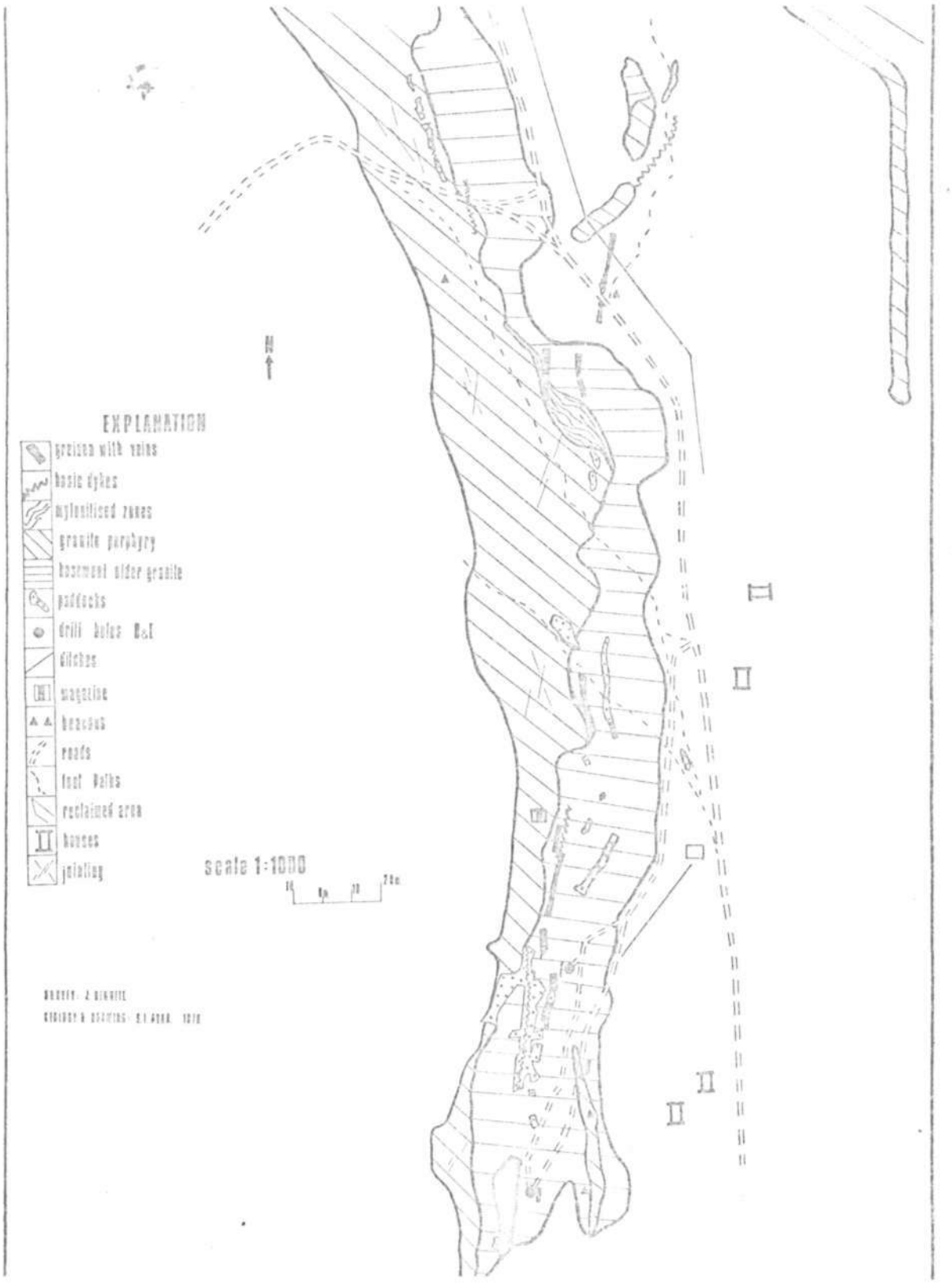
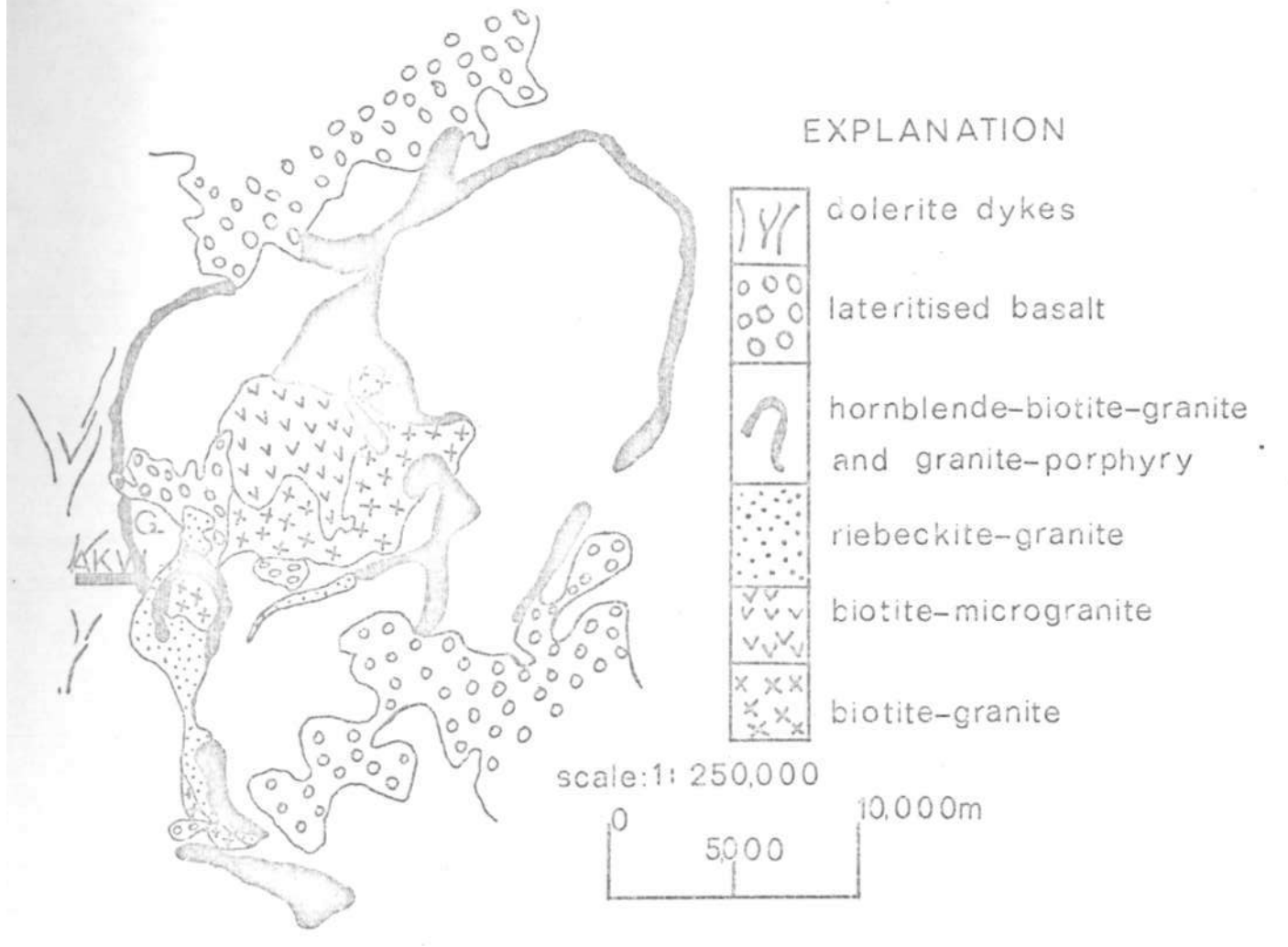

EXPLANATION
gneiss with veins
basic dykes
mylonitised zones
granite porphyry
basement older granite
paddocks
drill holes B&I
ditches
magazine
houses
roads
foot walks
reclaimed area
houses
jetating
scale 1:1000

Fig.3-2

GEOLOGICAL MAP OF ROP COMPLEX



Older Granite within which the mineralisation occurs in the form of greisen zones with feldspathic veins, and thin short zones of mylonitised rocks. The contacts are diffuse, except those of the granite porphyry and the Older Granite which may be sharp and regular (Fig. 3.1).

The Basement Older Granite

The Older Granite occupies about half of the mapped strip. In the Rop Complex, the Older Granites have been found to be generally of granodioritic composition and contain variable amounts of remnant streaks, schlieren and larger relic bodies of original gneisses enclosing scattered basic inclusions in some places (MacLeod et. al., 1971). The Older Granite in the mapped strip is mostly of gneissic texture with well defined foliation, biotite displaying remnants of less foliated zones. The foliation trends nearly N-S to N20^{o}E, and close to the contact with the granite porphyry, the rock has been mylonitised, displaying a brownish colour. Black zones due to greisenization are all restricted to the Older Granite which is weathered and, even at depth, it is difficult to obtain fresh samples from the available cores. The Older Granite tends to become coarser grained at depth and one sample shows a near porphyroblastic texture. The rock has been fractured and mylonitised, and contains shear surfaces with variable degrees of greisenisation and differing amounts of quartz and feldspar veining. In many places, small amounts of ore minerals can be observed in the hand specimen even in relatively unaltered Older Granite, althoughin insignificant amounts. The main minerals are feldspars, quartz and biotite with varying grain sizes.

Paddocks

The Older Granite has been worked in many places by the local people looking for tin. The most commonly worked zones are either along veins in the black greisens or along shear zones where the Older Granite has been mylonitised. In some zones, the workings have exposed narrow dolerite dykes both in the Older Granite and just at the contacts of the Older Granite with the granite porphyry. However the workings are not very deep since the greisen zones are not always continuous and in many cases only small amounts of tin can be found.

The Granite Porphyry.

The Granite Porphyry is part of the early Sho-granite-porphyry which is believed to have initiated the granitic cycle of the Rop Complex. This Sho-granite-porphyry ring dyke can be traced for about 19 km round the western perimeter of the Rop complex (Fig. 3.2). The rock has a variable texture and composition. In places, the granite-porphyry displays phenocrysts of feldspars and quartz which may be up to 1.5 cm and 3 mm respectively. Elsewhere, the rock attains granitic textures with large idiomorphic feldspars about 2 cm in diameter, while elsewhere along the dyke, the porphyry may contain ovoid, embayed feldspars, sometimes reaching lengths of more than 4 cm (MacLeod et al., 1971).

In the mapped strip, the granite porphyry trends approximately N-S but in the northern portion of the area it trends about 340^{o}. The contacts with the Older Granite are well defined and on the west of the dyke, the rock has a sharp contact with a vertical attitude. The contacts are characterised by a thin mylonitic zone usually associated

with a late dolerite dyke. Jointing is very pronounced with a dominant N-S orientation and a minor NW-SE trend. An average of 20 measurements on the major joint directions gave a value of 016°. It has been suggested that the jointing resulted from an east-west tensional field operating during emplacement of the Younger Granites (Weir; 1974). Some zones where small veins are associated with joint planes in the granite porphyry have also been worked for tin.

Faulting

No faults were observed in the mapped strip, however, close to this area, a major east-west fault has affected the granite porphyry. It is a dextral strike-slip fault, displaced about 130 m, with a small throw. Dixey (1945) has described several other similar faults in this area of the Rop Complex.

Greisens

The greisens occur in the Older Granite as small, discontinuous zones with transitional diffuse contacts into the Older Granite. The greisens are generally massive, fine grained and dark greenish black, although some pale brownish zones containing visible ore, particularly chalcopyrite are abundant and may themselves be greisens in shear planes. The greisens include a black, very fine grained, finely foliated variety, and a lighter coloured type with irregular schistosity. At depth, some of the greisens as well as greisenised Older Granite are intensely fractured. The greisens are often cut by numerous tiny pink feldspathic veins. Quartz veins and micaceous veins and knots may also be present, but these tend to be more frequent in the fractured greisenised Older Granite. Such quartz-mica veinlets are sometimes found in the granite porphyry, and where they occur, the rock is darkened for about

5 mm on both sides of the veins. These small dark zones in the granite porphyry may be a small scale greisenisation. The greisen zones are vertical and trend approximately 020° with the contained feldspathic veins also vertical and trending similarly. The greisens are variable in their visible ore mineral content and the pink feldspathic veins sometimes also carry visible ore. The different greisens from different horizons are shown in a core diagram (Fig. 3.3) together with zones of other rock types encountered in the drill cores.

Veins

Veinlets of quartz and dark micaceous material occur in the Older Granite. Most of the micaceous veinlets however predominate along the narrow shear planes. In the greisens quartz veins and feldspathic veins can be observed with the feldspathic veins predominating. The greisen veins are vertical, usually less than 2 cm wide and discontinuous. The veins predominantly trend 021° although a few may trend about 340°. Both quartz and feldspar veins contain visible ore as observed in the field.

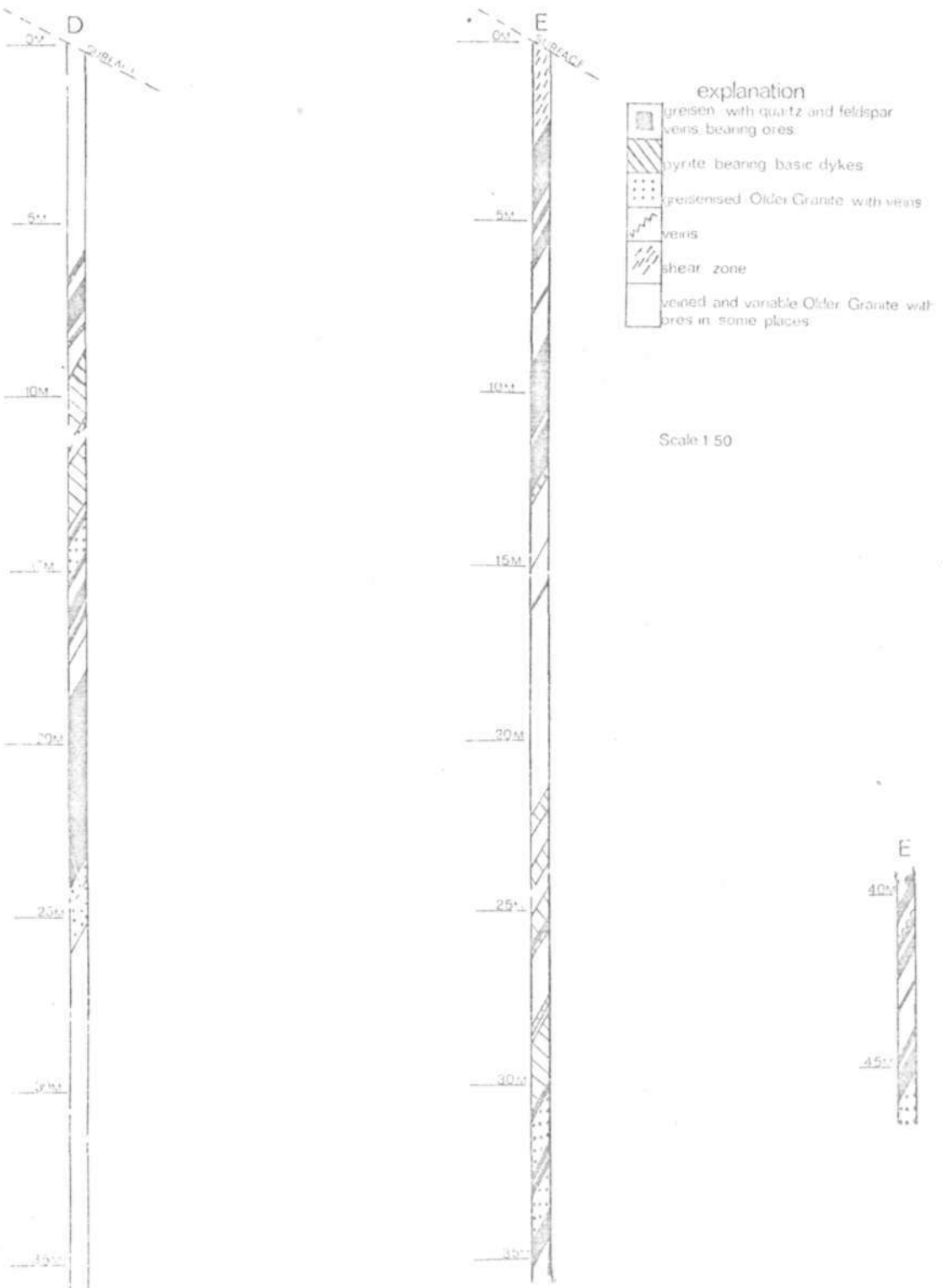
Basic dykes.

A great number of dolerite dykes cut the Younger Granites and adjoining areas of the basement complex in the south western part of the Rop Complex and Black (1971) has suggested that some of them may be connected with the extensive Tertiary volcanism which occurred in this area, while some are related to the Younger Granite cycle. About 3 km south of Gindi Akwati, one of such dykes is in the form of a plug with a diameter of about 150 m and is continuous with the Sho ring dyke. Most of the dykes are multiple

Figure 3.3 is a diagram showing the vertical sections of the two drill cores at Gindi Agwati. The diagram has be constructed based on the logging of the cores. Vertical scale as shown on the diagram.

FIG. 3.3

GINDI AKWATI CORE DIAGRAM
(based on hand specimen description of 'D' & 'E' cores [illegible])



intrusions with walls of the fine-grained dolerite and cores of the coarser porphyritic type (Black; 1971).

In the mapped strip, a swarm of the dolerite dykes has penetrated both the granite porphyry and the Older Granite. The dykes are parallel, trending approximately 020^{o} and are narrow, ranging in width from about 2 cm to 1 m (Fig. 3.3). On the surface, the dykes are highly weathered, and usually occur in contact with sheared zones of the Older Granite. The doleriites are very fine grained. The fresh samples at depth are dark bluish green and are impregnated with spots and dots of pyrite which is believed to be primary in the dolerites. Where contacts between the dolerite dykes and the Older Granite at depth are observed, the dolerites show definite chill zones usually about 5 mm wide. In such zones, the matrix is usually darker with visible colour changes in the minute feldspar crystals. Both feldspar and quartz veins are absent, but a few calcite veins associated with chlorite are present (Plate 4). The fresh samples of the rocks show neither deformation nor secondary mineralisation. The dolerite dykes are vertical and must be of late intrusion related to the Younger Granite cycle of magmatism.

Sequence of Events in the area

From field evidence as well as from petrographic evidence it can be deduced that the Older Granite is the oldest rock type in the area. During the emplacement of the granite porphyry the Older Granite was sheared and the mylonitised zones resulted. This shearing provided the essential near vertical channelways for hydrothermal fluids causing greisenisation. The quartz and feldspar veins were

then formed in the greisens, and finally the dolerite dykes were emplaced along some fractures. The order of events in the area is summarised below:-

Older Granite.

Granite porphyry emplacement.

Mylonitisation

Faulting

Greisenisation

emplacement of dolerite dykes.

3.1. Mineralogy and Petrology

The thin section study of the rocks in this area was restricted to cores at depth in case of the dolerite dykes, greisens and Older Granite since they were relatively fresher at depth. The cores did not intersect the Granite porphyry and as such no fresh samples could be obtained, so two samples from the surface have been described.

The Basement Older Granite

The Older Granite is medium to fine grained and extensively weathered. The rock is generally whitish with pink feldspathic veins while streaks of biotite occur giving it a relative dark colour.

In thin section, the rock has a even grained texture and is composed mainly of quartz, plagioclase, microcline and biotite. In some sections, a paler mica, probably muscovite is an accessory constituent. Accessory minerals vary from section to section but include apatite, sphene and zircon. The biotite has also been chloritised. Quartz occurs as clear, anhedral granular crystals or aggregates. Some of the quartz crystals form part of the rock matrix with feldspar and mica while a few of the grains have been enclosed by microcline crystals. Irregular recrystallised crystals of quartz also

occur, while rounded small crystals may occur as inclusions in feldspars. The proportion of quartz in the rock is similar to that of microcline while plagioclase is the dominant feldspar with compositions of albite-oligoclase (extinction angles between 0-15°). Both lamellae and Carlsbad twins are present, but the lamellae twins are thin and short with cloudy alteration. The microcline may be perthitic and the feldspars form about 67 per cent or more by volume of the rock. Biotite is the most abundant mica associated with occasional muscovite. The biotite forms subhedral to anhedral plates and aggregates. Shred-like aggregates also form lines round larger feldspar crystals or occur by themselves in lines like veins. A few grains of zircon and sphene have been observed in the mica aggregates in some sections.

The majority of the Older Granite sections show cataclasis and in such sections mica predominates, with the overall composition approaching that of the greisens. The large grains of feldspars and quartz have been broken down and fractured. Some of the feldspar crystals that survived the breakdown show strained effect with the twin lamellae well bent and the whole crystal may be bent similarly. Several rounded small grains of quartz and feldspar form dark-greyish matrix and sometimes these grains form discontinuous veinlets. The fractured crystals of feldspars and quartz contain inclusions of mica, topaz and most frequently fluorite, while veinlets may all be composed of secondary minerals. The biotite of the rock has been broken down and forms shredded aggregates which form discontinuous bands and winding lines surrounding streaky matrices of feldspars and quartz. Some of the mica may be muscovite, while chlorite may also be present. Fluorite has developed extensively in this form of the Older Granite where it occurs as individual masses associated with

mica, as well as inclusions in quartz and feldspar crystals. Sometimes sphalerite occurs associated with the mica and lying side by side with fluorite. Fine grains of the sphalerite, usually between 0.05-0.15 mm, may be found scattered all over the rock. In some cases one or two grains of cassiterite may also be present. Other minerals that may be found include topaz which is not abundant but contains so many inclusions that the crystals exhibit a perforated appearance. Oxides are found associated with the biotite flakes as clots, grains, streaks and brown gels.

Another form of the Older Granite is the highly sheared to near mylonitic variety. This is usually fine grained with more biotite than any other mineral. All the mica occurs as tiny flakes, usually along veinlets or lines and streaks, giving the rock a flow texture. Any feldspars that remain in this case occur only in the groundmass together with any quartz that may have remained from the original rock. The quartz here is mainly secondary recrystallised clear variety and occurs as short veinlets. The highly sheared rock has undergone some recrystallisation and is occasionally more mineralised than the greisens, particularly with sphalerite and chalcopyrite. Small fluorite and potash feldspar veins may be present but these too are usually discontinuous. Other veins composed mainly of secondary quartz are present and may be punctuated by zones of fluorite. Topaz may be abundant in some sections while massive fluorite occurs in other veins with a feldspar centre and a mica border. The largest veins contain a central feldspar zone with occasional quartz grains; the central feldspar may give way to fluorite and the alternation between fluorite and feldspars may only be interrupted

by sphalerite. The borders of such veins are usually lined by flakes of biotite and sometimes another pale mica. Sphalerite may occur in patches or as masses surrounded by fluorite and anhedral grains of opaques. In the veins with ore minerals, the general occurrence is that of a central sphalerite zone surrounded by fluorite which in turn may be surrounded by mica in association with opaques and occasional grains of cassiterite. Chalcopyrite may also occur in this association.

Nearly all the sections of the Older Granite contain fluorite, most of them contain topaz, all of them contain opaque minerals, a few of them contain crystals of zircon while sphalerite and cassiterite may or may not be present. The common phenomenon is for grains of sphalerite, topaz and fluorite to occur together in a bunch of biotite aggregates. There is also evidence of fluorite, mica and sometimes topaz replacing the original feldspars and quartz, and many of the quartz and feldspars of the original rock sometimes contain abundant inclusions of these new minerals.

The mylonitised shear planes of the Older Granite are well mineralised particularly with sphalerite and to a lesser extent chalcopyrite and cassiterite. In the field, it was found that most of the pitting (paddocks) is along such sheared zones. There is an association of quartz-sphalerite-fluorite-mica-topaz or feldspar-sphalerite-fluorite-mica-topaz type in the rocks. The occurrence of cassiterite in the sections is rare and any grains that occur are usually fine, hardly more than 0.1 mm in size. Topaz is mostly associated with quartz while a few grains of zircon are still preserved in the rocks.

It is evident that mineralising fluids accompanied

or followed the cataclasis of these rocks during which time topaz, fluorite and mica were introduced, and further replaced the original minerals in the rocks. The discontinuous bands and veinlets of quartz and feldspar aggregates are nearly parallel to the schistosity of the rocks while in some cases they form equal granular structureless aggregates or matrix. This means that the rocks were granulated under the influence of some directional stresses, determining the shape of the crystals, the structure and the textures of the rock. But the formation of discontinuous secondary veins and many new minerals indicates that, possibly recrystallisation took place and the hydrothermal fluids induced incipient greisenisation. Some new minerals may have formed as a result of the temperature and pressure changes associated with the fracturing and shearing. Some textures of the Older Granite are shown in photomicrographs (Plates 2 and 3).

The Granite Porphyry

The Granite Porphyry contains phenocrysts of feldspar and quartz and in hand specimen, clusters of biotite can be observed with specks of iron staining. In thin section the feldspars may be as large as 5 mm while those of quartz may be more than 1 mm. Other minerals include hornblende, biotite and accessory iron oxides, zircon, fluorite and sometimes allanite. The feldspars and quartz are irregular and have intergrown boundaries with the groundmass which is micrographic and forms about 50-60 per cent of the rock.

The feldspar of the rock is mainly orthoclase-perthite with abundant exsolution lamellae. The feldspar crystals may be small and clustered together. In some sections, phenocrysts of plagioclase may occur in addition to the orthoclase-perthites.

The bipyramidal quartz is also clustered, and in some sections secondary quartz may be abundant. Hornblende occurs as prismatic subhedral crystals and is highly altered. It is pleochroic from pale brown to reddish brown with some sections showing pale green tints. The hornblende appears to be secondary and may have been formed by alteration or replacement of initially crystallised pyroxene. The hornblende crystals are sometimes fibrous and it is thought that uralitisation may have occurred associated with the crushing, shearing and metasomatism in this area.

Biotite is not abundant in the rock, but forms clusters with opaques believed to be magnetite and ilmenite. Zircon crystals may also be present in some sections. Magnetite and ilmenite are abundant and are constantly associated with biotite. Fluorite is also present, usually developed in small veinlets of quartz and must have been introduced at a later stage than the consolidation of the granite. Crystals of allanite with haloes occur in some sections and are usually pleochroic from pale brown to dark brown with some crystals showing amorphous forms which may show some alteration. Two sections of the rock contained distinct aggregates of a pale brown mica, showing zoning, cracks and chloritised edges. Distorted veins of quartz sometimes with fluorite occur and grains of sphalerite and cassiterite have been observed in sections containing quartz veinlets. In field, tiny quartz veins accompanied by blackening of the vicinity of the veins are common. This and the fact that zones in the Granite porphyry have been pitted by the local people for tin indicates that some form of mineralisation occurs in the Granite porphyry.

The Sho-Granite porphyry dyke was the earliest of the granitic rocks in the Rop complex and its emplacement caused fracturing and shearing in the adjacent Older Granite, providing channelways for later fluid action associated with later biotite granites, resulting in the mineralisation contained in the Older Granite and to a lesser extent in the Granite porphyry as well. Black (1971) suggested that this rock filled many of the initial interlocking fractures in the Rop complex Sho-system, and the original pattern has been largely obliterated by the succeeding granite intrusions in the central area of the complex.

Greisens

The greisen zones are few on the surface, but several zones have been intersected at depth by the two cores, and they have varying thicknesses (Fig. 3.3). The greisens have been recalculated to their actual thicknesses from the core diagram, and they range in thickness from 8.60 cm to 368.10 cm in Core D and from 6.50 cm to 177.90 cm in Core E (Table 3.1). The greisen is a product of the fractured Older Granite and the transition from the Older Granite to greisen is gradational with increasing micaceous material from the Older Granite into the greisen. The greisen is black, very fine grained and usually massive except where effects of mylonitisation can be observed, in which case the greisen is more cleaved. The greisens are usually traversed by pink feldspathic veins which carry visible ore in hand specimen. Greisens from the cores are fresh and contain veins as at the surface but are generally fractured.

In thin section, the greisen is a micaceous quartz-feldspar-topaz-fluorite rock. The greisen has a variable texture and in some cases the abundance of particular minerals

Table 3.1. Depths to Greisen zones and their thicknesses.

'E' CORES				'D' CORES			
Core depth to Greis-en	Vertical depth to Greisen M	Traversed thickness in cm.	Actual Greisen thick-ness cm	core depth to Greisen in M.	Vertical depth to Greisen in M.	Traversed thickness in cm.	Actual thick-ness in cm.
2.60m	2.25	92.5	79.9				
3.75	3.25	65.0	56.3				
4.85	4.20	20.0	17.3				
5.50	4.76	57.5	49.8	6.20	5.37	25	21.6
7.23	6.26	17.5	15.1	6.95	6.02	85	73.6
8.80	7.62	205.0	177.5				
11.10	9.61	135.0	116.9	11.15	9.66	45	39
25.65	22.21	10.0	8.6				
30.45	26.37	7.5	6.5	13.50	11.69	15	13
32.15	27.84	25.0	21.6	14.75	12.77	10	8.6
32.55	28.19	25.0	21.6	15.50	13.42	55	47.6
34.15	29.57	80.0	69.3	16.30	14.12	20	17.3
35.00	30.31	40.0	34.6	18.10	15.67	425	368.1
36.05	31.22	17.5	15.1	22.50	19.49	95	82.3
36.60	31.70	45.0	39.0				
37.83	32.76	15.0	13.0				
39.28	34.01	25.0	21.6				
39.85	34.51	77.5	67.1				

is also variable and the complete transition from greisenised Older Granite to greisen indistinct. The main minerals of the greisen are mica, quartz, topaz, sphalerite and fluorite, but where veining is present, feldspars are also present and may attain large proportions. The micas of the greisen are biotite, a pale to colourless mica and sometimes muscovite. Chlorite is also present while sericite may or may not be present.

The Micas

The biotite is fine grained with small flakes, pleochroic from pale brown to dark brown, and the flakes usually occur in aligned clusters surrounding feldspathic veinlets or quartz aggregates which are sometimes associated with the feldspathic veins. The muscovite also occurs as scaly shreds and aggregates but a few tabular grains also occur. The third variety of mica is

colourless, forming tabular and prismatic crystals. Some of the crystals are thick and zoned with a pale core and a dark margin. Some of the crystals are radiating with fan like boundaries and are believed to be lepidolite and a product of biotite replacement. Bowden (1975) has however stated that the transformation of biotites in the biotite granites of Nigerian Younger Granite province produces siderophyllite and protolithionite. Optical properties were determined on the greisen micas and the results are given (Table 3.2).

Table 3.2. Optical Properties of Micas; Gindi Akwati Greisens

Property	muscovite 1	?lepidolite 2	biotite 3	biotite 4
Interference fig.	opt-ve	opt-ve	opt-ve	opt-ve
n	1.570-1.614	1.561-1.606	1.541-1.628	1.573-1.637
2V	30-45°	30°-40°	5-30°	5°-25°
Ext. Z a	0-4°	3-8°	0-3°	0-3°
X	pale-greenish	colourless	pale-yellow	pale straw yellow
Y	pale-green	pale with brown tints	dark-brown	pale-greenish
Z	green	colourless to greyish	dark-brown-dark-brownish green	-green
Absorption	X < Y < Z	Y > X ≥ Z	X < Y ≥ Z	X < Y < Z

Although no modal analysis was carried out on the greisens due to their fine grained nature, the proportion of mica in the greisens is always up to 50 percent by volume of the rock. The greisen owes its black colour to the dark greenish colour of the chlorite that may locally become abundant as well as the fine aggregates of biotite and muscovite.

Quartz

The quartz of the greisens is almost all secondary except in a few cores where traces of the Older Granite are

present. The amount of quartz in the greisens varies from section to section, but hardly reaches 20 percent by volume of the rock. The quartz occurs mainly in the veins and discontinuous veinlets associated with feldspars. In some sections large anhedral crystals of quartz occur, while in others smaller crystals occur associated with topaz. Some veins and veinlets of quartz also occur alone particularly in the more fractured greisens.

Feldspathic veins

The feldspar veins are small, varying from about 0.1 mm in width to about 0.3 mm, usually irregular with short branches. The feldspar content of the greisens is restricted to these veins except in a few cases and in the case where remnants of the Older Granite can be found. Some of the veins contain both quartz and feldspars but the quartz may occur more on the borders of feldspars which are usually at the centre of the veins. In some cases the feldspar veins may crosscut other quartz bearing veins. Some of the feldspathic veins show zones with central albite crystals growing inwards usually surrounded by perthitic feldspars which form the walls of the veins and these are in turn surrounded by an alternating fluorite and mica zone. These veins sometimes contain large spherulitic masses of sphalerite and fluorite, with small grains of cassiterite in or around the sphalerite.

Sphalerite

By far the most common ore mineral in the greisens is sphalerite. Massive brown and grey sphalerite occurs as patches all over the rock, while smaller masses occur around and on the veins. In all cases there is an association of the sphalerite with fluorite which is also massive. Grains of

sphalerite are also disseminated in the greisen and are associated with cassiterite. The sphalerite is sometimes associated with opaques, fluorite and quartz, in which case topaz becomes abundant. In some cases, sphalerite occurs at the centre of veins of quartz bordered by fluorite which is in turn bordered by mica with crystals of cassiterite. In such occurrences, sphalerite masses are as large as 6 mm.

Cassiterite

Cassiterite is generally subordinate to sphalerite in amount in the greisens. Cassiterite most commonly occurs in mica pods together with a little fluorite on the margins of the quartz and sometimes feldspar veins. Small grains of cassiterite also occur in the sphalerite masses where the cassiterite grains hardly exceed 2 mm in size. The rest of the cassiterite occurs as fine grains scattered in the rocks either in the mica matrix or associated with groups of fluorite-sphalerite-opaques occurring together.

Chalcopyrite

Chalcopyrite occurs mainly in the more cleaved variety of the greisens, usually as large euhedral crystals in constant association with sphalerite and iron oxides. The fine grained greisens hardly contain any chalcopyrite. The amount of chalcopyrite is also small compared to sphalerite, and is absent in most of the greisens.

Fluorite

Fluorite is present in all the samples examined and in some sections it forms up to 20 percent by volume of the rock. Where there is abundant sphalerite, masses of fluorite also occur. Fluorite also occurs in large amounts in the Older Granite that has not been greisenised. In some cases fluorite occurs in the feldspar-quartz veins associated with sphalerite,

or it may occur on the borders of the veins associated with mica and cassiterite grains. However the amount of fluorite decreases where topaz is abundant and this phenomenon is observed mostly in the fine grained greisens in which the colourless mica has started to develop. Some veins are composed wholly of fluorite but such veins are usually discontinuous.

Topaz

Topaz is also abundant in some of the sections and occurs associated with quartz and contains many inclusions. It attains high proportions in sections that have developed large tabular crystals of colourless micas, and is usually more abundant in the mineralised and less fluorine bearing sections.

Other common minerals in the greisens are iron oxides and zircon. The iron oxides are sometimes abundant, and are either associated with sphalerite or micas, where they occur in the form of dots, smears, clots, streaks and brown gels. Small amounts of monazite and greenockite are also present. In all cases, greenockite occurs with sphalerite. Wolfram also occurs in small amounts and is restricted to the quartz and quartz-feldspar veins. Little amounts of pyrite also occur while bornite suspected from hand specimen has not been observed in thin sections.

Several mineral associations have been observed in the greisens. Mica is however the most common constituent of the greisens. Quartz, feldspars and fluorite are also always present, while topaz may or may not be present. The associations in which the ore minerals may occur are:-

(1) Cassiterite-sphalerite-quartz-fluorite-mica- topaz; in this association, the mineral that may sometimes be present

is feldspars, usually angular grains of cloudy orthoclase.

(2) Cassiterite-sphalerite-quartz-fluorite-mica-feldspars; in this association, topaz which is sometimes present in the association is absent.

(3) Cassiterite-sphalerite-feldspar-fluorite-mica; in this association, both quartz and topaz are absent.

(4) Cassiterite-sphalerite-quartz-fluorite-mica-iron oxides; in this association feldspars are absent, while iron oxides have been introduced in the association.

In the last association, some of the iron oxides may include chalcopyrite, and the association is thought to be of the quartz-mica-fluorite-chalcopyrite-sphalerite-cassiterite type. This association is however rare in the rocks, and occurs mostly in the fractured greisens or near shear planes. Of all the associations mentioned above, the most common is the quartz-mica-topaz-fluorite-sphalerite-cassiterite type. Close to this and next in abundance is the feldspar-mica-fluorite-sphalerite-cassiterite type, and sometimes abundant sphalerite. These two types of associations form the mode of occurrence of the ore minerals, and the Gindi Akwati lode may be described as belonging to them.

It is clear that most of the important deposits of sphalerite, cassiterite and to a lesser extent chalcopyrite were introduced with the pink perthitic-orthoclase-albite veins. Some of the ores were introduced before some shearing occurred, and when movement has stopped, further introduction of ores by hydrothermal fluids continued, forming veins of quartz and feldspars. This is so since some of the fluorite-quartz veins have been deformed and strained, while later unstrained patches, veinlets and aggregates of quartz and mica with ore minerals are also present.

The Dolerite Dykes

The basic dykes are dark to bluish-green and very fine grained. In thin section, the dolerites contain plagioclase, calcite, epidote, quartz and abundant secondary chlorite. The plagioclase occurs in the groundmass as long prismatic crystals which are usually euhedral. In some sections the plagioclase crystals become larger and in such areas, chlorite decreases considerably. Crystals may locally become as large as 4 mm in length and the plagioclase is believed to be mainly labradorite with 2V between 70°-90° and extinction angles vary from about 30°-40°.

Calcite occurs in the groundmass as grains and spherulitic crystals while some prismatic crystals may be associated with quartz also in the groundmass. Epidote occurs mainly as grains but some sections contain fine columnar aggregates and where the rock becomes coarse grained, well developed pseudo-hexagonal crystals of epidote occur. In most cases, chlorite may mask the epidote crystal outlines.

Pyrite occurs as euhedral triangular coarse crystals associated with other opaques in the form of tiny grains and dots. Quartz occurs in the groundmass and in some cases it is associated with calcite. Chlorite is abundant and much of the chlorite is secondary replacement after other minerals. A few crystals of biotite and augite are also present in some sections.

The dolerites contain very few calcite veins which have formed as a result of alteration (Plate 4), by groundwater action. The only ore mineral observed in the dolerites is pyrite, which primarily crystallised with the rocks, and is abundant in some sections. No effects of alteration by late

hydrothermal fluids were observed, and there are no signs of strain or shearing. At the contact with the Older Granite where chilling has occurred, small veinlets of mica and quartz in the Older Granite can be observed to terminate sharply exactly at the dolerite boundary (Plate 5). This is evidence that the hydrothermal ore bearing fluids which caused greisenisation and veining in the Older Granite occurred before the emplacement of the dolerite dykes. The dykes were however emplaced along the fracture planes in the Older Granite, and on the surface where pitting for cassiterite is common along the shear zones, many of the dykes have been exposed. The dolerite dykes may either be connected with the extensive Tertiary volcanism which occurred in this area or they may be associated with the Younger Granite cycle that has caused greisenisation and mineralisation in the Older Granite in this area.

Chemical Composition of the dolerite

Four of the dolerite samples were analysed for their major and some trace elements. The results and their Barth Mesonorms are given here together with the average abundances of trace elements in basalts (Krauskopf; 1967) for comparison (Table 3.3 and 3.4).

The analyses compare well with basic rocks elsewhere in this province (MacLeod et al. 1971). The silica content of the dolerites ranges from 45.02 to 48.18 percent, and only one sample contains quartz in its norm. This shows that the dolerites are basaltic characterised by low SiO_2 content with high FeO, MgO and CaO and low Na_2O and K_2O. The total iron content is relatively higher than the total iron in basalts of this province. This can be accounted for by the pyrite content of the rocks. However the amount of sulphur is very low compared to the amount of pyrite observed in thin section.

This low sulphur content may be due to the detection limit in the method used for analysis since the method has a high lower detection limit.

The basaltic rocks however are enriched in some of the trace elements analysed for compared to the average compositions of basalts. The most significant increases occur in Zn and Li. Zn is the main metal in the ore minerals that occur in this area. Similarly the micas of the greisens in this area are rich in Li. This suggests that the ore fluids that caused mineralisation in this area may have affected the dolerite rocks. However the dolerite dykes show no sign of secondary alteration or enrichment. It can be explained that the origin of the dolerites must have been closely associated with the granitic magma from where the mineralising fluids originated. It is possible that the hydrothermal fluids may have affected the basaltic magma in the liquid phase before it finally solidified as dolerite rocks. The field evidence combined with the chemical composition and ore minerals in the rocks point out well that the dykes were emplaced after the mineralisation and greisenisation in the Older Granite.

3.2. Geochemistry

There is a considerable published analytical chemical data on the Nigerian Younger Granite rocks (Jacobson et al; 1958; Bowden and Turner, 1974; Bowden, Whitley and Van Breemen, 1975), and a large collection has also been published in the Bulletin of the Geological Survey of Nigeria No. 32 (MacLeod et al. 1971). However, little chemical data can be found on the altered wallrocks and greisens associated with mineralisation in this province. Almost all of the Nigerian

Table 3.3. Chemical Analysis and Barth Mesonorms of dolerites.

	D_2 12.60	E_3 22.20	E_3 22.74	E_4 29.52
SiO_2	46.73	45.02	48.18	46.32
Al_2O_3	14.54	14.21	15.44	15.46
TiO_2	3.28	3.10	3.69	3.61
Fe_2O_3	1.68	1.56	1.06	1.36
FeO	15.14	13.99	9.48	12.23
MnO	0.21	0.28	0.14	0.38
MgO	6.50	5.92	3.29	5.95
CaO	5.73	8.01	9.38	7.47
Na_2O	2.63	2.80	4.17	3.16
K_2O	1.55	1.63	1.93	1.37
H_2O^+	0.57	1.57	0.83	0.39
H_2O^-	0.81	1.27	0.41	0.28
P_2O_5	0.42	0.28	0.54	0.49
F	0.01	trace	0.04	0.03
S	0.11	0.10	0.10	0.10
	99.30	99.64	98.53	98.55
Less O	0.04	0.06	0.03	0.06
Total	99.26	99.58	98.50	98.49
Quartz	0.86	0.00	0.00	0.00
Orthoclase	0.00	0.00	2.39	0.00
Albite	23.49	22.14	32.06	28.80
Anorthite	14.19	21.27	17.70	21.61
Olivine	0.00	6.55	0.00	8.04
Hypersthene	29.42	11.23	0.00	14.97
Actinolite	0.00	0.00	2.65	0.00
Edenite	0.00	0.00	17.05	0.00
Biotite	14.58	15.31	14.40	13.15
Corundum	3.60	0.00	0.00	1.09
Sphene	6.82	6.44	7.70	7.66
Magnetite	1.75	1.62	1.11	1.44
Apatite	0.87	0.58	1.13	1.04
Water	4.31	5.65	3.83	2.10

Table 3.4. Selected Trace Element Analysis of dolerites.

Elements ppm	D_2 12.60	E_3 22.20	E_3 22.74	E_4 29.52	Average Composition of basalts.
Cu	36	33	56	33	100
Pb	20	18	42	31	5
Zn	3071	346	470	195	100
Sn	30	40	70	40	1
Cd	1	2	2	2	0.2
Li	3/6	240	392	223	10
Be	8	7	23	7	0.5
U	4	6	4	9	0.6
Th	2	2	4	11	2.2

In Tables 3.3 and 3.4

D_2 12.60 = Dolerite sample from D core at 12.60m. depth.

The rest from E core. No. after E represent depths at which sample is taken

Analysts: S.I. Abaa. R. Batchelor. (1976).

granites contain between 70 and 77 percent silica with similar small variations in the other major oxides. The greisens in which ore minerals occur have been analysed and their chemical composition discussed.

Major Element Chemistry

15 samples from Core D and Core E were analysed for their major elements and the results are presented (Table 3.5) together with their Barth mesonorms.

The silica content of the rocks is highly depleted compared to the Older Granite and greisens elsewhere in this province. This low silica content is manifested in the mineralogy of the rocks in which greisenisation has produced mica-fluorite-topaz rocks rather than an increase in quartz.

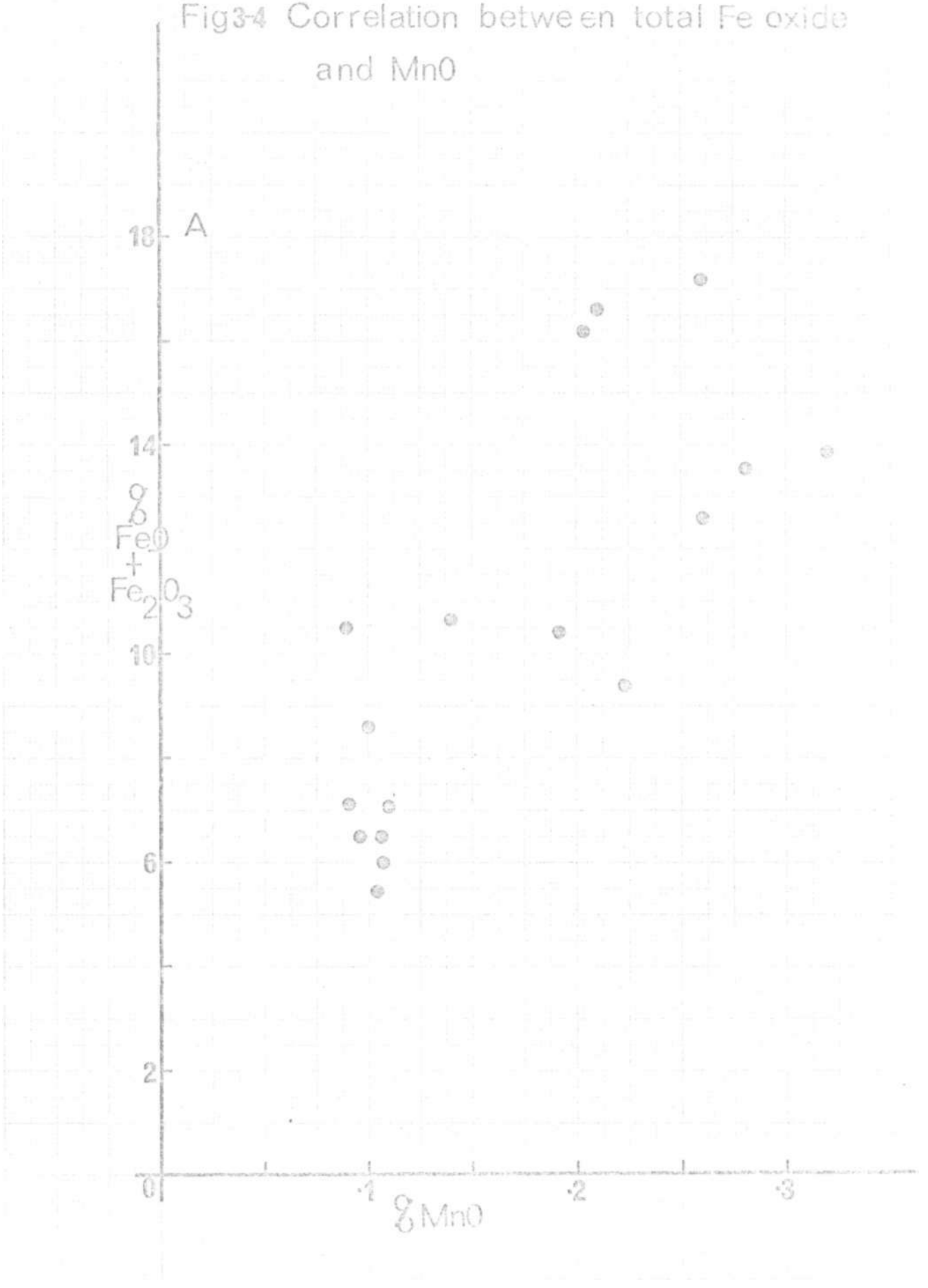
Furthermore the veins that occur in the greisens and greisenised Older Granite contain more feldspars than quartz. The silica content of the rocks ranges from 41.24 percent in a greisen proper to 56.71 percent in greisenised Older Granite. Alumina is variable in the samples and shows a slight increase with increasing silica and its content varies from 13.05 to 20.75 percent except one sample (D_1 8.45) which has an anomalous value of 6.53 percent and a corresponding low in silica of 23.69 percent. In hand specimen, the sample contains visible white and purple fluorite which is responsible for this anomaly and has been further reflected in the high content of lime and fluorine which are up to 39.30 and 17.68 percent respectively. Titania is enriched in the rocks compared with the normal Older Granite content and can be attributed to the presence of iron oxides including ilmenite, as well as a possible substitution in the lattices of other minerals such as magnetite and possible brookite (TiO_2). The rocks are also enriched in total iron ($FeO + Fe_2O_3$) with values ranging from 5.32 to 23.10 percent. The high iron content is accounted for by sphalerite, the micas of the rocks; biotite, muscovite, sericite, and a colourless mica. Chlorite also contains Fe^{2+} and more iron could come from other minerals such as pyrite, ilmenite, magnetite and chalcopyrite to add up to make such high values of total iron in the rocks. Manganese is not high in the rocks, with a range from 0.10 to 0.38 percent. There is, however, a slight correlation between the manganese content and the iron content (Fig. 3.4a) and as the total iron increases, the manganese content also increases. This relationship can be attributed to the occurrence of wolfram in the greisen and greisenised Older Granite veins.

Table 3.5. Chemical Analysis and Barth Mesonorms of greisens from Gindi Akwati

	E_1 2.96	E_2 8.93	E_4 32.10	E_5 39	E_5 46.1	E_6 46.57	D_1
SiO_2	41.35	43.56	55.40	54.74	43.06	62.60	41.
TiO_2	0.30	1.70	0.51	0.52	0.78	0.26	1.
Al_2O_3	15.91	14.33	16.83	16.99	19.45	13.65	13.
Fe_2O_3	1.73	1.60	0.65	0.74	1.61	0.72	2.
FeO	15.61	14.35	5.81	6.63	14.44	6.46	20.
MnO	0.26	0.32	0.11	0.12	0.21	0.09	0.
MgO	1.51	8.61	2.33	2.31	2.86	1.79	7.
CaO	8.79	4.81	4.17	3.26	1.22	2.95	1.
Na_2O	3.26	2.60	5.60	5.12	4.11	2.06	1.
K_2O	2.78	4.20	2.53	3.51	7.13	5.48	8.
P_2O_5	0.31	0.24	0.13	0.16	0.42	0.22	0.
H_2O^+	0.58	0.34	0.31	1.30	1.18	1.48	0.
H_2O^-	0.33	0.09	0.18	0.63	0.93	0.59	0.
F	4.84	2.71	2.55	3.75	1.78	1.35	1.
SO_2	0.12	0.12	0.12	0.10	0.22	0.13	0.
	97.66	99.69	97.36	99.90	99.40	99.82	100.
Less O	0.06	0.08	0.03	0.91	0.38	0.07	1.
Total	97.60	99.61	97.33	98.99	99.02	99.75	99.
Quartz		0.00	2.80	4.58	0.00	21.57	0.
Orthoclase		0.00	6.43	6.91	16.77	20.03	0.
Albite		22.25	51.61	43.02	15.42	17.97	10.
Anorthite		14.76	13.68	12.19	0.57	11.49	-
Nepheline		-	-	-	11.88		31.
Olivine		10.01	-	-	-		28.
Hypersthene		0.66	-	-	-		Rib 11.
Actinolite		-	7.29	0.41	-	0.69	-
Edenite		2.11	-	-	-		-
Biotite		38.97	14.26	20.00	37.51	18.30	8.
Sphene		3.49	1.09	1.02	C 4.96	0.53	2.
Magnetite		1.64	0.70	0.72	1.61	0.73	-
Apatite		0.49	0.28	0.31	0.84	0.45	0.
Water		1.64	1.56	5.59	6.23	6.22	3.

E_1 to E_6 are samples from Core E. D_1 to D_4 are from Core D. Numbers after E_{1-6} ar

Fig3-4 Correlation between total Fe oxide and MnO



Magnesia is also enriched in the rocks ranging from 0.93-8.61 percent, and the enrichment can be accounted for by high content of the micas as well as chlorite. Lime is also high, ranging from 1.04 to 39.30%. The high lime content is mainly due to the high content of fluorite as well as some contribution from some plagioclase in the feldspathic veins, and in case of the greisenised Older Granite, from some of the plagioclase of the original Older Granite that has not been replaced. There is also a corresponding increase in fluorine content of the rocks with increasing lime (Fig. 3.4b). Soda is low in the rocks and shows an increase with increasing silica; the values ranging from 1.12 to 7.60 percent (Fig. 3.4c). Since there is more silica in the less greisenised Older Granite it is an indication that the contribution to soda content is mainly from minerals of the original Older Granite as well as some contribution from the albite crystals developed in the feldspar veins and from substitutions in the lattices of other minerals. Potash is generally higher than soda and is particularly high in the greisens with many veins. Potash values range from 1.98-8.81 percent with the maximum value occurring in the sample with the minimum value for soda, although there is no good correlation between increasing potash and decreasing soda. The high values of potash can be attributed to the feldspathic veins which contain mainly perthitic-orthoclase; since these values are also highest in the greisens containing more of such veins. There is also a slight increase in potash with decreasing silica (Fig. 3.4d) particularly in the fine grained greisen. This corresponds with increasing greisenisation. The more intensely greisenised rocks contain more feldspathic veins

Fig 3-4 Correlation between Fluorine and CaO

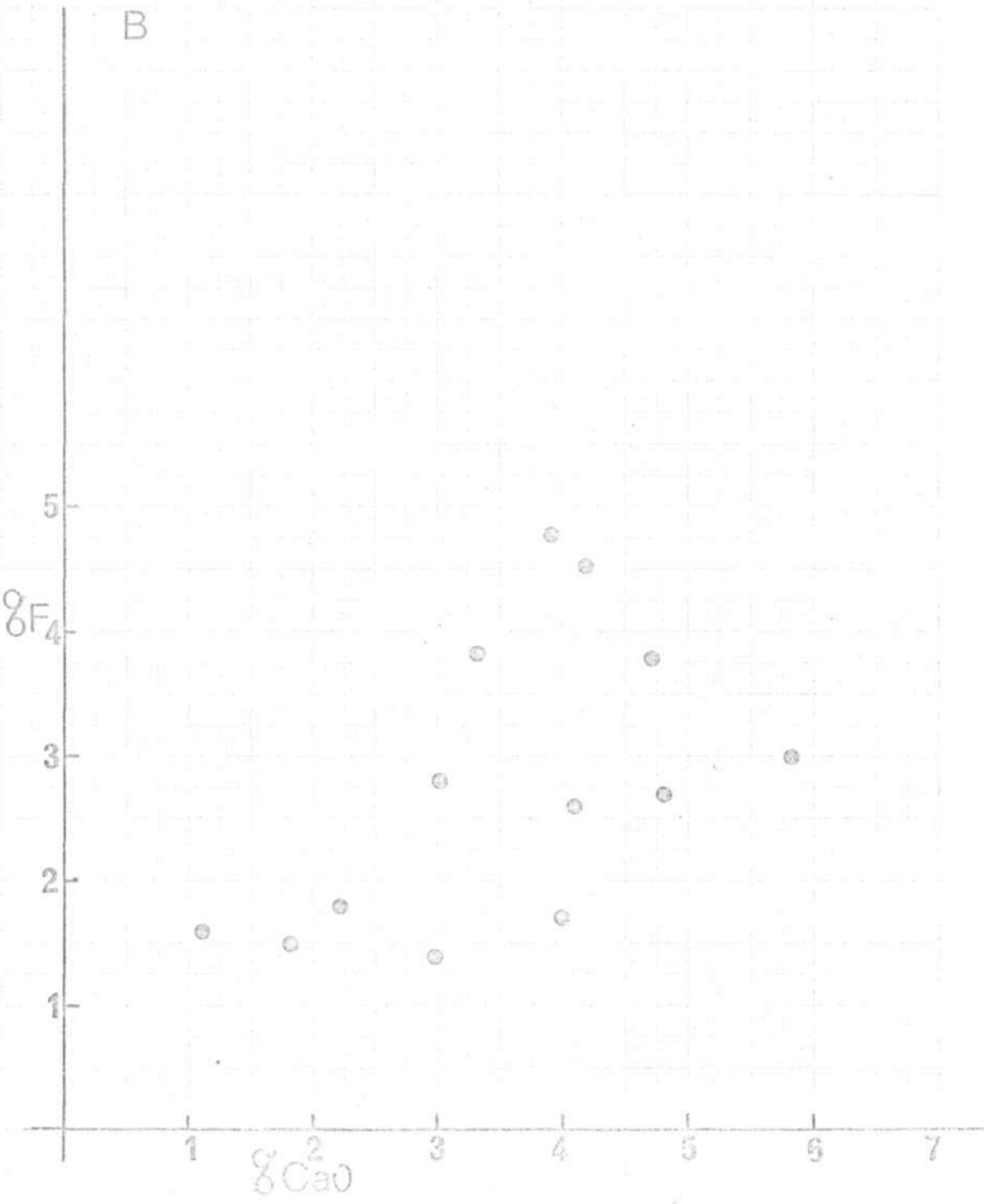


Fig 3-4 Oxide variation diagrams

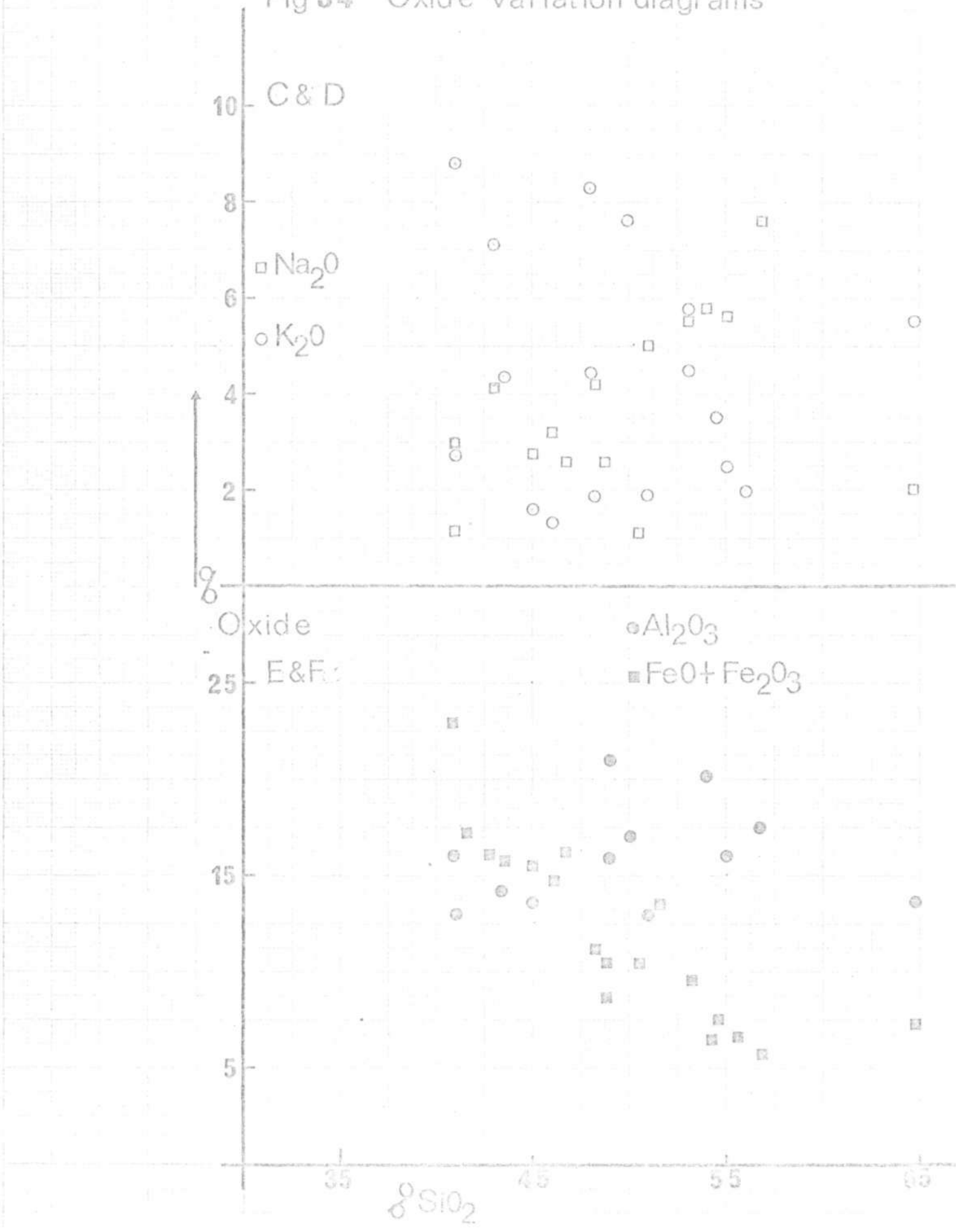
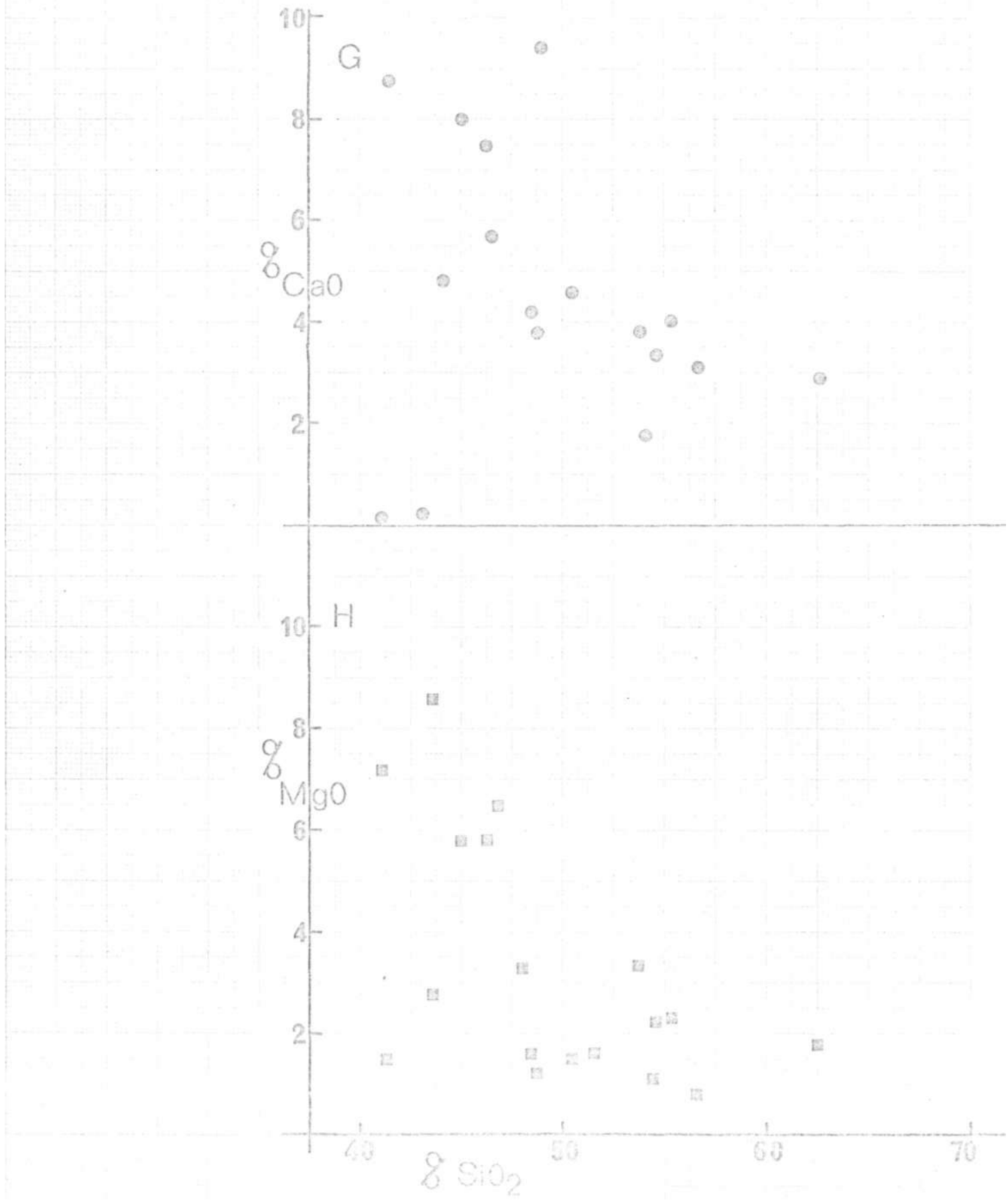


Fig3-4 Oxide variation diagrams



and since these veins contain mainly perthitic-orthoclase, the content of potash and hance the amount of veins is an indication of the degree of greisenisation. Oxides of the major elements have been plotted against the silica content (Fig. 3.4), and as the silica decreases, i.e. as greisenisation increases;

(1) Alumina slightly decreases (Fig. 3.4e)

(2) Total iron (FeO + Fe_2O_3) increases distinctly (Fig. 3.4f)

(3) lime distinctly increases, i.e. increasing fluorite (Fig. 3.4g)

(4) Magnesia increases i.e. increasing mica content (Fig. 3.4h)

(5) Soda also decreases i.e. with increasing soda, and increasing silica the greisenisation is less intense (Fig. 3.4c)

(6) Potash increases i.e. there are more feldspathic veins which is an indication of increased greisenisation (Fig. 3.4d)

(7) Fluorine increases i.e. with increasing greisenisation, more lime is released from the plagioclase of the original granite, and fluorite is formed. This corresponds with decreasing silica (Fig. 3.4g).

Trace Element Chemistry

Selected trace elements have been analysed for in the greisens and greisenised Older Granite to estimate the extent of mineralisation. The results have been reported in parts per million (ppm) (Table 3.6). It is not possible to correlate these results with values in the original granite since virtually all the original granite samples were affected by mineralisation. The concentration of the elements show a good correlation with increasing feldspathic and quartz veins in the greisens. The Cu content of the samples ranges from

Table 3.6. Selected trace Element analysis, Gindi Akwati Greisens.

Sample		Cu	Pb	Zn	Sn	Cd	Li	Be	U	Th
E_1	2.96	7.66	12	19,600	1330	100	156	194	16	8
E_2	8.93	41	40	2,400	110	12	407	30	6	2
E_4	32.10	6	30	497	150	2	1133	57	22	27
E_5	39.00	4	18	347	130	1	1638	142	18	54
E_5	40.10	1060	45	1200	2400	5	4217	9	22	11
E_6	40.57	3600	18	341	22,130	2	1122	39	6	7
D_1	7.20	3	30	613	130	1	1853	26	4	2
D_1	8.45	50	822	583	2230	4	34	102	5	10
D_2	15.70	870	138	6372	3100	44	1664	101	6	10
D_3	18.28	184	30	12,460	110	48	4207	9	7	4
D_3	19.50	6889	30	908	6200	3	535	5	6	15
D_3	21.50	2319	10	37690	2250	145	3141	41	9	11
D_3	23.57	10	40	1100	530	3	521	63	15	8
D_4	24.54	470	15	9636	450	43	935	66	6	2
D_4	26.55	516	10	4100	250	21	67	69	13	7

E_1-E_6 are samples from core E and the numbers after them represent depths at which the samples are taken in metres.

D_1-D_4 are samples from Core D and the numbers after them represent depths in metres at which the samples are taken.

Analysts: S.I. Abaa and R. Batchelor (1976).

3-6889 ppm with the maximum value occurring in a greisenised Older Granite with feldspathic veins and is highly cleaved. The minimum value of 3 ppm occurs in a homogeneous greisen made up of mainly micas. This sample also has very high value for Li, which is an indication of the amount of micas present. This Cu content corresponds well

with the field occurrence of chalcopyrite, which concentrates more in this type of greisen. The average Cu content in 15 samples is however 1119 ppm. Pb values are low in the samples with a maximum value of 822 ppm. The area is not well mineralised with lead ores, and in all the cores examined, galena was observed only in one thin vein about 0.5 mm wide. Zn is the most mineralised in the greisens, as sphalerite varying in colour from brown to reddish-brown and grey. The highest value of 37690 ppm Pb occurs in a greisen with cross cutting veins of quartz and feldspars, and the minimum value of 341 ppm also occurs in a greisen composed of nearly only micas. The mean value of Zn in 15 samples is 7442 ppm. The Sn content of the samples is low with a range of values from 110-22130 ppm, the highest value occurring in a greisen with both quartz and feldspar veins. The mean value of Sn in 15 samples is 2767 ppm. Li is enriched in the greisens and this is attributed to the lithium bearing micas which make up more than 70 percent of the greisens. Be is not high in the samples with a range of 5-194 ppm and shows no visible correlation with either Li or any of the other elements. U and Th are depleted in the samples with a mean value of 11 ppm U and 11 ppm Th and a range from 4-22 ppm U and 2-54 ppm Th. These values show a depletion compared with values of 50-150 ppm found in the plagioclase bearing rocks of this province.

The trace elements with economic concentrations here are Zn and Sn. The samples are however not proportionately enriched in the elements. One sample may contain high values for Zn and Cu but low Sn while Sn and Cu may be enriched in a sample with low Zn. The ore concentrations do not bear any visible correlation with one another and the ratios of one

element to another is very variable in different samples (Table 3.7). This may be an indication of the varying compositions of the mineralisation fluids. During mineralisation, the fluids were pulsating with varying elemental concentration, resulting in some greisen zones being more mineralised in a particular ore than the other, as well as the formation of many thin individual greisen zones.

Effects of wall-rock Composition

The ore fluids that introduced ore minerals in the Older Granite at Gindi Akwati were of magmatic origin associated with biotite granite magmatism with a composition similar to that at Ririwai. Both fissure deposition and replacement ore formation occurred in a similar manner that occurred at Ririwai. However the ore fluids affected the biotite granite with which they were associated at Ririwai while at Gindi Akwati, the ore fluids were foreign in the Older Granite. The main differences are that whereas there is abundant fluorite and topaz at Gindi Akwati, these minerals are not much at Ririwai. Again, whereas these are mainly feldspathic veins associated with greisens at Gindi Akwati, at Ririwai the veins are quartz bearing with hardly any feldspathic veins.

Since the mineralising fluids had similar composition, then the host rock have played a role which resulted in the differences. Perhaps other factors too, like pressure and temperature as well as depth of erosion and emplacement of the biotite granites with which the ore fluids were associated are important. At Gindi Akwati the biotite granite responsible for the ore fluids may be at greater depths and the ore fluids possibly have introduced ores in the granite at depth, but some of the fluids escaped to higher levels in the crust and thus

Table 3.7. Ratios of Some Trace Elements in the Greisens.

Sample	Zn:Sn	Cu:Sn	Zn:Cu	Zn:Li	Sn:Li
E_1 2.96	15:1	1:2	25:1	126:1	9:1
E_2 8.93	22:1	1:3	58:1	6:1	1:3
E_4 32.10	3:1	1:25	82:1	1:2	1:10
E_5 39	3:1	1:33	86:1	1:5	1:10
E_5 40.1	1:2	1:3	1:1	1:3	1:2
E_6 40:57	1:50	1:5	1:10	1:3	20:1
D_1 7.20	5:1	1:50	204:1	1:3	1:10
D_1 8.45	1:3	1:50	11:1	17:1	66:1
D_2 15.70	2:1	1:3	7:1	4:1	2:1
D_3 18.28	113:1	2:1	67:1	3:1	1:33
D_3 19:50	1:5	1:1	1:7	2:1	12:1
D_3 21.50	16:1	1:1	16:1	12:1	1:1
D_3 23.57	2:1	1:50	110:1	2:1	1:1
D_4 24.54	21:1	1:1	20:1	10:1	1:2
D_4 26.25	16:1	2:1	8:1	61:1	4:1

affected the Older Granite. This may explain why there is no large ore zone at Gindi Akwati since only little amounts of ore fluids escaped from the deeper biotite granite.

Since replacement is important in the two areas some of the differences can be explained by reaction of wall rocks with mineralising fluids. As seen from the composition of the altered wall rocks and the veins in the greisens, the ore fluids were possibly rich in alkalis. At Ririwai the ore fluids reacting with wall rocks released potash from greisens and combined with the original potash in the fluids formed potash feldspars in the reddened granite. The silica thus

released by destruction of feldspars in the biotite granite that has been greisenised concentrated in the fluids and was later deposited in the greisens and veins as quartz. But at Gindi Akwati the potash released by the formation of greisens as well as potash originally in the fluids combined with silica in the fluids to form perthitic-orthoclase which was later deposited in veins in the greisens. This explains why, at Gindi Akwati feldspar veins are associated with greisens, but at Ririwai quartz veins occur.

In case of fluorite, it is observed that at Gindi Akwati, the Older Granite has a granodioritic composition which means that as the replacement of the feldspars of the Older Granite commenced, lime was released and the lime reacted with fluorine in the fluids to form fluorite. But at Ririwai lime is lacking in the biotite granite and as such the fluorine in the fluids mainly combined with Li and other ions like iron and Al and Mg to form micas. This may explain the abundance of fluorite at Gindi Akwati and the lack of fluorite at Ririwai. At Ririwai topaz is lacking since the available alumina and fluorite went into the formation of Li micas while silica went into the formation of quartz. At Gindi Akwati it has been found that as greisenisation proceeded, the amount of fluorite decreased slightly while topaz increased, and furthermore more plagioclase formed at the centres of the feldspar veins in the greisens. The decrease in fluorite was possibly due to further reaction in which some fluorite was destroyed. The fluorine thus released from the fluorite destroyed went into the formation of topaz together with Al and silica remaining in the fluids afte the formation of perthitic-orthoclase feldspars in the veins. The lime released from the partial destruction of fluorite combined with some alumina and silica in the fluids and formed the later albite-plagioclase which has been deposited at the

centres of the feldspathic veins. The formation of the perthitic-orthoclase, plagioclase and topaz may further explain the depletion in silica in the greisens at Gindi Akwati compared to the silica enrichment in the greisens and veins as quartz at Ririwai.

Mineralisation

Mineralisation in the Rop Complex in which the Gindi Akwati lode occurs is extensive and ore minerals which occur include columbite, wolfram and cassiterite while smaller quantities of fergusonite, thorite, zircon, monazite, xenotime, beryllium minerals, molybdenite, sphalerite, chalcopyrite, pyrite and galena have also been reported (MacLeod et al., 1971; Bowden et al., 1974 and Williams et al., 1956). At Gindi Akwati, a lode which is richer in sphalerite than cassiterite occurs in the Older Granite gneiss at the contact with a Granite Porphyry ring dyke in a zone of crushed and mylonitised rocks. The ore minerals occur in greisen veins and zones in the Older Granite as well as dispersed in the fractured Older Granite.

The origin of the mineralisation is the same with that of Ririwai but the mode of occurrence is slightly different. At Ririwai the mineral association is a typical quartz-mica-sphalerite-cassiterite-sulphide type while at Gindi Akwati two main types of mineral associations occur, namely the quartz-mica-topaz-fluorite-sphalerite-cassiterite-sulphide and the feldspar-mica-fluorite-sphalerite-cassiterite-sulphide types. At Gindi Akwati, the mineralising fluids contained less siliceous fluids. The anions and cations were transported in fluorine rich fluids and were later deposited along joints,

fractures and foliation of the Older Granite. Post joint replacement also played an important role of ore formation. The ore minerals do not show any zoning and the greisen zones are randomly distributed in a vertical section in the host Older Granite (Fig. 3.3). No massive ores were formed however sphalerite may have been deposited before other ores since it usually occurs with fluorite surrounded by other minerals. The ores present are sphalerite, chalcopyrite, pyrite, little galena, and wolfram. The ore minerals show an increase with depth as can be seen from (Table 3.8) where tin, zinc and copper values have been allotted to the greisen zones from which they come. It is possible that at greater depth than investigated, large greisens and pegmatitic-like veins which are more mineralised may occur. From core D (Fig. 3.3) the greisen intersected at a depth of 6.02m is 73.6 cm thick and contains 0.22% tin, 0.06% Zinc and 0.005% Copper. After this greisen zone, three thin greisen zones ranging from 8 cm to 39 cm in thickness occur. A fourth greisen zone at 13.42m depth is 47.6 cm thick and contains 0.31% tin, 0.64% Zinc and 0.09% Copper. The largest greisen zone intersected is at a depth of 15.67m and is 3.68m thick, containing 0.71% tin, 3.77% Zinc and 0.69% Copper and is the most mineralised zone. The greisen zone is thick compared to others and it is possible that it may contain large veins with much ore, but such veins were not intersected. In core E the most mineralised greisen zone occurs at a depth of 34.51m and is 67.1 cm thick. Although this zone is comparatively narrow, it contains 2.21% tin, by far the largest value obtained in all the cores analysed. This indicates the way in which the ores may be more concentrated at greater depth. It also indicates the way a narrow greisen zone may

be more mineralised than a larger one. This is further indicated by the range in values for tin, zinc, copper and manganese in four cases from the same greisen zone as indicated below.

Table 3.8. Analysis of Sn, Zn and Cu in different greisen zones.

E Cores depth	Sn in ppm	Zn ppm	Cu ppm	D Cores depth	Sn ppm	Zn ppm	Cu ppm
E 2.6m	1330	19600	766	6.95m	2230	583	3 50
					130	613	
E 8.80m	110	2400	41				
				D15.50m	3100	6372	870
E 32.14m	150	497	6				
				D18.10m	6200 110	908	6889; 184
E 37.83m	130	347	4		7130 and	12460	99 and
					2250	13760 and	2319
E 39.85m	22130	1200 and				37690	
	and 2400	341	3600 and 1060	D 225m	530	1100	10

Sample	D_3 18.28m	19.50m	20.0m	21.5m	Range
% tin	0.01	0.62	0.71	0.23	0.01 - 0.71
% zinc	1.25	0.09	1.38	3.77	0.09 - 3.77
% copper	0.02	0.69	0.01	0.23	0.01 - 0.69
% manganese	0.09	0.05	0.05	0.05	0.05 - 0.09

Generally the Gindi Akwati is richer in zinc than other ores. The ores are concentrated in the greisens as well as disseminated in the crushed and sheared Older Granite.

The Ore fluids

Although there is no biotite granite outcrop in the vicinity of this mineralised zone, it is clear that the mineralisation is directly related to the final stages of consolidation of biotite granites. It would therefore be suggested that there may be a biotite granite batholith at depth in this area, during

whose crystallisation, fluorine, zinc, tin and copper concentrated in the residual fluids. This increased the vapour pressure of the fluids, as well as magmatic heat acting as a driving force, caused the hydrothermal fluids with their dissolved ions to rise through the cooling biotite granite at depth. Some of the fluids escaped from the biotite granite and rose through the fractures and shear planes earlier produced by the emplacement of the Granite porphyry ring dyke. The fluids also utilised the joints and foliations in the Older Granite.

The hydrothermal fluids were rich in alkalis but relatively poor in siliceous components since most of the veins contain feldspars and little quartz. The contents of the fluids played an important role of replacement, converting the feldspars, quartz and some of the biotite of the original Older Granite into other micas as well as other minerals like fluorite, chlorite, sericite and topaz. This produced the mica-quartz-topaz-fluorite-sphalerite-cassiterite-sulphides and the feldspar-fluorite-mica-cassiterite-sphalerite-sulphide mineral associations observed here. This replacement mineralisation also produced the mica rich greisens rather than the quartz rich greisens observed at Ririwai.

CHAPTER 4

DUTSEN WAI

General Description

The Dutsen Wai intrusion is a small granite massif near Dutsen Wai village in the north-west corner of the Nigerian Younger Granite province and occupies an area of 6.34 km^2. It is situated about 64 km E-S-E of Zaria City and located at $8^{\circ}13'E$ to $8^{\circ}15'E$ and $10^{\circ}50'N$ to $10^{\circ}52'N$ on sheet 125NW of Northern Nigeria Survey Ordnance map 1966. The intrusion rises to about 120 m above the surrounding Basement rocks and plains. The intrusion is one of the most westerly of the Jurassic Younger Granites (Fig. 1.1) that occur in a 200 km wide north-south zone in central Nigeria, concentrating more around the Jos Plateau (Bowden et al. 1976). The flat land surrounding the intrusion is composed mainly of gneisses, migmatites and recent alluvials. The massif has sharp contacts with the Basement rocks which are low lying outcrops. The Basement rocks however rise steeply at the contacts with the intrusion in the south-west and southern parts of the intrusion, reaching about 50 m high in some places. The Younger Granites have gentle dips towards and under the Basement rocks, and Gakaiye and Sweeney (1974) have described the Dutsen Wai intrusion as a high level, thin, tabular body with subsurface extension of felsic material, dominantly biotite granite, well beyond the outcrop limits of the complex in all directions. Further away from the intrusion, the migmatites and gneisses give way to predominantly recent alluvials extending far and wide in all directions uninterrupted. The nearest Younger Granite intrusion to the Dutsen Wai massif is Banke, about 17 km away.

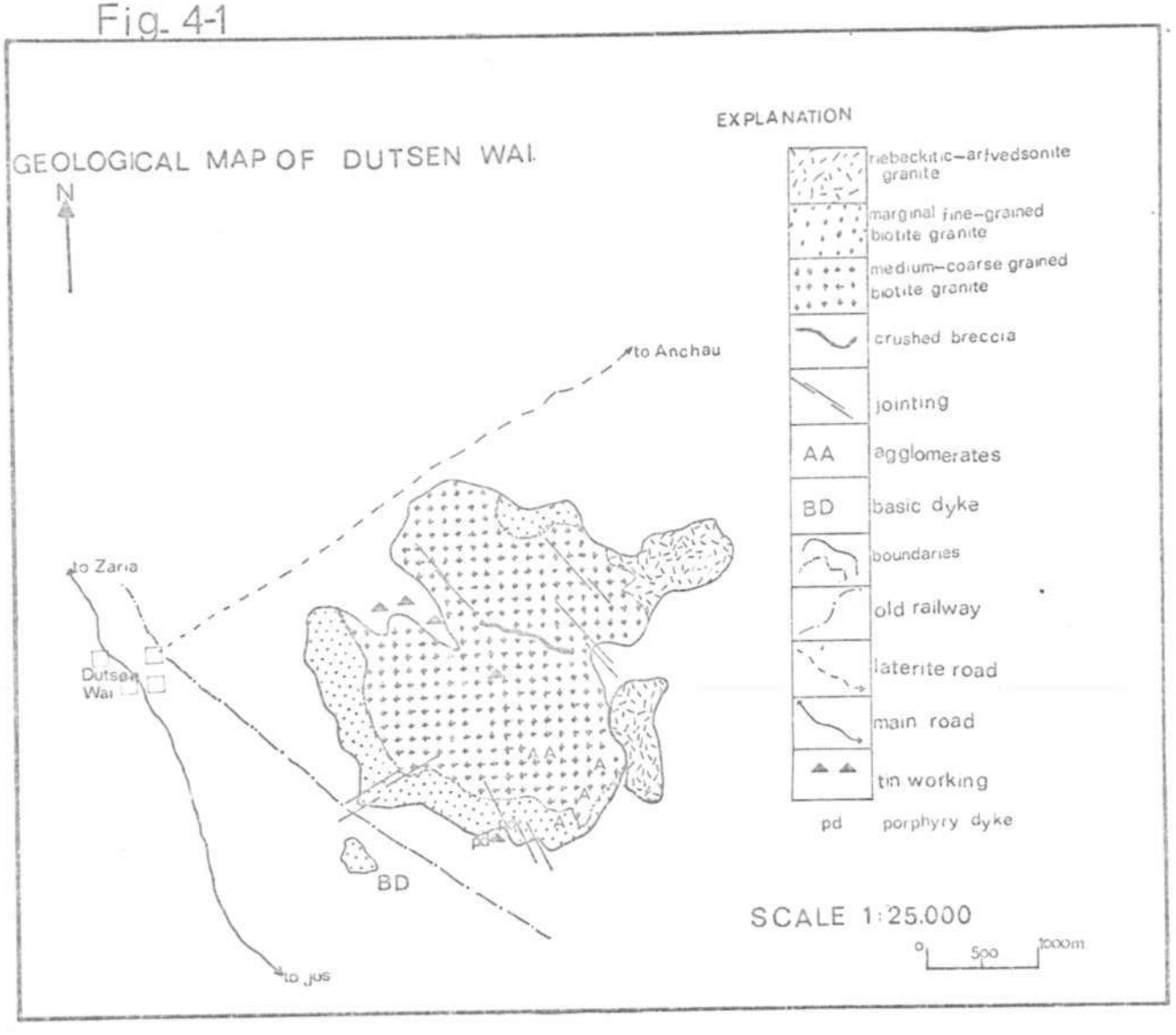
The most distinctive structure in the intrusion is the

prominent NE-SE and NS joint systems. The major joint zone trends NW-SE giving rise to a flat bottomed wide valley draining the centre of the complex to the north-west. This joint zone appears to be a fault zone and a brecciated rock occurs along its strike (Fig. 4.1). This supposed fault has further displaced the massif into two portions, the northern and the southern part which rises highest.

Very few dark thin veins about 1 mm wide are associated with the biotite granite. These veins are barren and very micaceous. Some thin biotite microgranitic dykes also associated with the main biotite granite cut the granite as well as extending into the Basement rocks. The general trend of the whole massif is north-south but as is the case with most or all of the Nigerian Younger Granite complexes, the Dutsen Wai intrusion is a near ring structure. The difference here is that the intrusion is very small and not all the normal rock types found in the large ring complexes are present. Turner (1963) described the structure of Nigerian Ring-Centres as having an early phase of volcanic activity which was probably brought to a close by the major cauldron-subsidence: thereafter the intrusive phase marked the waning of igneous activity, the emplacement of granites by block-subsidence into a shrinking magma-chamber, so that successive intrusions had smaller diameters and were situated nearer the centre of the complex.

At Dutsen Wai, there is evidence of such a relationship, although only little amounts of volcanic rocks are found at this complex. Three major igneous units typical of the Younger Granite ring complexes are found here. These are the volcanics, the albite-riebeckitic-arfvedsonite granite and the biotite granites. Remnants of an initial volcanic phase in the form of agglomerates and explosion breccia occur at the southern flanks, south eastern

Fig. 4-1


GEOLOGICAL MAP OF DUTSEN WAI
N
EXPLANATION
riebeckitic–arfvedsonite granite
marginal fine–grained biotite granite
medium–coarse grained biotite granite
crushed breccia
jointing
AA agglomerates
BD basic dyke
boundaries
old railway
laterite road
main road
tin working
pd porphyry dyke
to Anchau
to Zaria
Dutsen Wai
to Jos
BD
SCALE 1:25,000
0 500 1000m

flanks and on top of the eastern peak (Fig. 4.1). Then the albite-riebeckitic-arfvedsonite granite occurs in two areas in contact with the biotite granite on the eastern border of the massif. A thin porphyry dyke (1.5 cm wide) is also exposed in a tin working in the south while another basic dyke, 2 cm wide can be observed away from the main massif across the old railway in a small outcrop of Basement.

4.1. Petrology and Mineralogy

The Dutsen Wai intrusion is composed of two types of high level, non-orogenic alkaline granites with only traces of a volcanic phase. The granites are described here in order of abundance.

Biotite Granite

There are two textural variations of the biotite granite. The larger (aerial extent) variety is a medium grained pinkish granite which grades into a fine grained outer zone believed to be a chilled phase. The medium grained biotite granite occupies more than 70 percent of the whole intrusion. On the surface (in field) the fine grained chilled biotite granite contains stains of iron oxides, probably ilmenite and patches of quartz irregularly distributed in the mass. This chilled margin is in contact with the country rocks, particularly on the western edge, although in places the country rocks are not exposed and the medium grained chilled biotite granite is in contact with superficial cover.

In thin sections both granite varieties have the same mineral composition. The variation is observed in the chilled phase where the contained biotite has been highly chloritised with individual biotite crystals becoming more greenish with increase in associated oxides and brown gels.

The feldspars

The biotite granite contains dominantly, microcline-microperthite, small discrete crystals of albite and patchy perthitic replacement intergrowths of albite. The groundmass feldspars are mainly albite grains and microcline. Some sections contain more orthoclase which displays varied exsolution lamellae, patchy perthites accompanied by few clear separate microcline. Some of the potash feldspar of the perthites is cloudy effect of kaolinisation, while individual albitic grains are clear. The plagioclase of the biotite granite has a composition Ab_{95}-An_5 with extinction angles between 13° and 20° measured on twin lamellae and 2V between 70-90° (mean of 10 measurements).

Lamellae exsolution perthites are abundant and with orthoclase they form about 55 percent (Table 4.1) modal volume of the biotite granite. These perthite often occur with narrow rims of small albite laths along crystal interfaces.

Table 4.1. Modal analysis of the biotite granite, Dutsen Wai.

	DW 7	DW 8	DW 16	Mean
Quartz	35.9	34.8	36.3	35.7
Orthoclase-Microperthites	54.1	55.9	54.8	54.9
Albite	5.1	4.8	5.6	5.2
Biotite	1.7	3.5	2.3	2.5
Fe oxides	2.3	0.1	0.2	0.9
Zircon	0.1	0.1	0.1	0.1
Fluorite	0.2	0.4	0.3	0.3

This occurrence of discrete albite may be due to unmixing of the two alkali feldspars being continued beyond the perthitic

stage (Tuttle and Bowen; 1958). Exsolution perthites are present in other Nigerian granites and in many members of the group, exsolution has proceeded so that free albite is abundant, often as quite large crystals (MacLeod et al; 1971).

Quartz

Quartz is next to feldspars in abundance in the biotite granite. Large crystals occur with the feldspars as well as in the groundmass. The large crystals occur clustered together or arranged in arcuate form between the larger perthites. Sometimes the quartz crystals appear as trails of anhedral grains. Quartz appears to have crystallised in two phases with initial crystals clustered and a later quartz replacing feldspars. From the modal analysis (Table 4.1) the biotite granite contains 35.7 percent free quartz.

Biotite

The biotite of the granite has been chloritised, particularly in the chilled phase. In this case the biotite has become greenish with pale brown borders associated with oxides, and its fine cleavage nearly all destroyed. The normal biotite is pleochroic from pale yellowish to dark brown. Some sections contain biotite which is pleochroic from pale yellow to dark brownish green and in some positions it is nearly opaque. Optical properties determined on some of the biotites are given (Table 4.2).

Bowden and Turner (1974) have described biotites from the Nigerian Younger Granite Province as falling into two groups and belonging to the trioctahedral micas. These are the micas of the perthitic peralkaline and non-peralkaline granites, which are iron rich members of the phlogopite-annite-siderophyllite series, and those of the albitic granites together with the

Table 4.2. Optical properties of biotites.

	DW 7	DW 8	DW 16
n_γ	1.675	1.664	1.683
n_ω	1.616	1.610	1.603
$n_\gamma - n_\omega$	0.059	0.054	0.080
2V	very small $0-3^\circ$	$2 - 8^\circ$	$3 - 7^\circ$
Ext. $Z \wedge a$	$0 - 5^\circ$	$0 - 4^\circ$	$0 - 5^\circ$
X	straw yellow	pale yellow	pale straw yellow
Y	pale green	dark brown	dark brown
Z	dark green	nearly opaque	dark brownish green
Absorption	$X < Y < Z$	$X < Y < Z$	$X < Y \leq Z$
Interference figure	biaxial - ve	-ve	- ve

DW 7 Biotite from fine grained chilled biotite granite Dutsen Wai.

DW 8 and DW 16 biotites from medium grained biotite granite, Dutsen Wai

n determined using Abbe Refractometer. S.I. Abaa (1976).

somewhat paler coloured micas of the greisens which are lithium poor members of the siderophyllite-protolithionite-zinnwaldite-lepidolites isomorphous series. The biotite here is however thought to be lepidomelane ($2V \sim 5 - 15^\circ$). The biotite generally has strong absorption, very dark and cleaved. It contains many haloes probably caused by alpha-particle bombardment from small zircon crystals containing radioactive meterials. It is also possible that the haloes are due to minute radioactive cores within the biotite itself.

Accessory minerals

The biotite granite contains accessory minerals which

include zircon and fluorite. Fluorite is found associated with some biotite crystals. Zircon is randomly distributed in the rock as individual grains but is not usually abundant, and may not be observed in some sections. A few grains of very small euhedral monazite were observed in some sections, within a quartz matrix. Only one section showed grains of sphene, while all the sections examined contained some iron oxides (ilmenite magnetite and haematite). No cassiterite or any other ore minerals were observed in the examined sections.

The proportion of minerals described above is nearly constant in all the sections examined. The minerals in the rock tend to form aggregates of like crystals and the grain size ranges from 1 mm in quartz and biotite to about 6 mm in a single perthite. Greenwood (1961) has described the commonest feature and most diagnostic of the Nigerian biotite granite minerals as forming aggregates of like crystals, clots of perhaps a dozen quartz crystals, or biotite flakes, or feldspars occurring together with grain sizes ranging from 1-5 mm with single perthites up to 10 mm.

The Albite-riebeckitic-arfvedsonite-aegirine granite

This rock type is medium grained with an even texture and greyish white colour. Towards the southern edge it has developed a thin pegmatitic contact and in general it is subordinate in aerial extent to the biotite granite.

In thin sections the rock contains large crystals of quartz, orthoclase and riebeckitic-arfvedsonite, sometimes intergrown with aegirine. Sections that contain clear well twinned albite laths and prismatic crystals contain little or no aegirine at all.

Quartz

Quartz crystals are anhedral and large usually occurring together with individual crystals not well terminated. The sections with aegirine contain less strained quartz crystals while in the sections with no aegirine both strained and unstrained clear secondary crystallised quartz is present. The amount of modal quartz is about the same as that in the biotite granite, and ranges from 28-35 percent with a mean of 32 percent for three samples (Table 4.3).

Feldspars

Microcline-microperthite is the most abundant feldspar in the rock, but the rock contains more modal albite than in the biotite granite (Table 4.3). Some sections contain small amounts of clear late crystallised microcline. Such sections contain rounded smaller perthites while individual grains of lath-like albite and microcline with prismatic habit are hardly more than 1 mm. In some sections where aegirine appears the orthoclase-perthite and microperthites are very large while albite forms intergrowths with microcline or orthoclase-microperthites. Modal analysis of the rocks shows that the feldspars form about 60% by volume of the rock (Table 4.3).

Aegirine and Riebeckitic-arfvedsonite

In the sections containing both aegirine and riebeckitic-arfvedsonite, the two minerals are of equal mounts and are always intergrown. The aegirine appears both in centres of the riebeckitic-arfvedsonite and around the borders. The two minerals appear to have crystallised together, at the same time and at the expense of each other. Some crystals contain alternate laths or flakes of aegirine and riebeckitic-arfvedsonite (Plate 6). The riebeckitic-arfvedsonite crystallised with

Table 4.3. Modal Analysis of Albite-riebeckitic-arfvedsonite granites.

	DW 11	DW 12	DW 13	Mean
Quartz	32.4	35.3	28.5	32.1
Orthoclase-microperthite	37.9	43.3	52.6	44.6
Albite	23.6	15.3	9.7	16.2
Biotite	-	-	-	-
Riebeckitic-Arfd.	3.2	2.4	3.9	3.0
Aegirine	-	0.1	3.8	1.3
Fe oxides	-	-	-	-
Zircon	trace	0.1	0.2	0.1
Fluorite	0.1	0.5	0.2	0.3
Pyrochlore	0.4	0.3	0.2	0.3
Cryolite	1.4	1.6	0.2	1.0

DW 11 and DW 12. Albite-riebeckitic-arfvedsonite granite Dutsen Wai.

DW 13 Albite-riebeckitic-arfvedsonite-aegirine granite, Dutsen Wai.

aegirine appearing both in the cores and around the borders of the mineral suggesting that fluctuating chemical conditions in the magma may have effected partial transformation of one mineral into the other. The riebeckitic-arfvedsonite is pleochroic from pale greenish yellow to light-blue-grey or pale blue. The aegirine is pleochroic from pale green to pale-greenish-yellow or faint green. Some amphiboles from other Nigerian alkaline rocks are pleochroic from indigo to light greenish-yellow, deep blue to dark grey-blue to yellowish (Borley; 1963). Optical properties of the aegirine and the riebeckitic-arfvedsonite are given (Table 4.4 and 4.5) together

with those from other areas (Borley; 1963).

In the well recrystallised sections the riebeckitic-arfvedsonite occurs more in form of rectangular or thin prismatic small grains, and in such sections there is little or no aegirine. In the aegirine bearing sections, the aegirine and the riebeckitic-arfvedsonite crystals occur as spongy and interstitial plates and laths, sometimes more than 1 mm in size.

Table 4.4. Optical Properties of Aegirine

	DW 13	DW 14	3	4
Interference figure	biaxial + ve	biaxial + ve	-	-
N	1.765-1.827	1.766-1.838	1.769-1.826	1.769-1.838
2V	50-70°	75°	n.d.	n.d.
Ext. X∧C	2-4°	3-5°	2.3	5.4
X	light green	light green	light green	Light green
Y	light green-ish-yellow	pale green-ish yellow	light-green-ish yellow	n.d.
Z	faint green	faint green	faint green	faint green
Absorption	X≥Y>Z	X≥Y>Z	X>Y>Z	X>Z

DW 13. Aegirine, from albite-riebeckitic-arfvedsonite aegirine granite, Dutsen Wai.

DW 14. Aegirine, from albitite-riebeckitic-arfvedsonite-aegirine granite, Dutsen Wai.

3. Aegirine, from riebeckite-aegirine granite, Liruei X 575.

4. Aegirine, from albite-riebeckite-granite, Liruei X 1356.

DW 13 and DW 14. determined by S.I. Abaa (1976).

No. 3 and 4. taken from Jacobson, MacLeod and Black (1958) Page 18.

Table 4.5. Optical Properties of Riebeckitic-Arfvedsonites.

	DW 11	DW 12	DW 13	4	5
n	1.687-1.694	1.681-1.703	1.692-1.712	1.677-1.693	1.691-1.696
2V	~ 90°	80-90°	75-90°	high	n.d.
Ext. X ∧ c	8°	7-8°	7-9°	4° ± 1°	0°
X	dark blue	dark blue	dark blue	Indigo	dark blue green
Y	light blue	pale blue	light blue grey	blue	dark grey blue
Z	light greenish yellow	pale-yellow-green	pale-green - yellow	light-green - yellow	light straw
Absorption	X > Y > Z	X > Y > Z	X > Y > Z	-	-

DW11 & DW 12. riebeckitic-arfvedsonite, from albite-riebeckitic-arfvedsonite granite. Dutsen Wai.

DW 13. riebeckitic-arfvedsonite, from albite-riebeckitic-arfvedsonite-aegirine granite. Dutsen Wai.

4. Amphibole from albite-riebeckite granite PB3 Ka + fo R. Liruei complex.

5. Amphibole, from aegirine-riebeckite granite PB 7. Liruei complex.

DW 11-13. determined by S.I. Abaa (1976).

No 4 and 5 taken from Borley (1963) P 367.

Accessory minerals

Accessory minerals vary in some of the sections except for fluorite and zircon which are present in all the sections examined. Pyrochlore occurs in the highly albitised variety of the rock and varies from faint brownish white to grey and usually occurs round the albite and riebeckitic-arfvedsonite crystal boundaries. The crystals are anhedral with irregular

boundaries. Zircon crystals are few and scattered. In some sections zircons are metamict due to radioactive bombardment, and it has been suggested that this bombardment could be by atoms of Uranium and/or thorium contained within the mineral or sometimes in minerals in contact with the zircon (Bowden and Turner, 1974; Whitten and Brooks, 1972). Fluorite is present in all the sections examined and occurs in cracks along quartz grains and at other crystal boundaries. Cryolite and amblygonite are also present while elsewhere Bowden and Jones (1975) have reported both cryolite, pyrochlore, amblygonite and thomsenolite in albite-riebeckitic-arfvedsonite granite. In some of the riebeckitic-arfvedsonite granites in this province thorite and ilmenite occur as accessory minerals (Jacobson et al, 1958), while Borley (1976) has described aemigmatite in an aegirine riebeckite granite from Liruei.

Although the albite-riebeckitic-arfvedsonite granite at Dutsen Wai is a single intrusion, it is rather inhomogenous texturally and mineralogically. In an area of about 100 m^2 alone, both the greyish fine grained and the medium grained less greyish varieties can be found. The finer grained variety is however more abundant near the contact with the biotite granite, and could be interpreted as a chilled facies, or a recrystallised zone due to the emplacement of the biotite granite. In the field, it is difficult to distinguish the two varieties of the albite-riebeckitic-arfvedsonite granite as different intrusions. Mineralogically, the greyish finer grained variety contains little or no aegirine and appears to be more recrystallised, more albitised and more mineralised with the accessory minerals pyrochlore and cryolite. None

of the sections examined contained biotite, although in other localities in this province biotite sometimes occurs in the rocks.

In the albite-riebeckitic-arfvedsonite-granite, the orthoclase-perthite and quartz must have crystallised before the riebeckitic-arfvedsonite and the aegirine where it occurs. As in the biotite granite, both exsolution and replacement textures are found but much more albite is present in the rock than in the biotite granite. A large proportion of deuteric albite (An 5) has replaced earlier formed feldspars and amphiboles resulting in the high albite content. Bowden (1974) stated that in peralkaline rocks, late stage albitisation may be locally severe with a large proportion of deuteric albite replacing earlier formed feldspars and amphiboles. He used the high albite content in these rocks to suggest that hydrothermal modification, by solutions of albitic-acmitic composition has been an important process. It appears also that quartz crystallised as a different phase after the perthite had crystallised, and a later generation of quartz crystallised as well as formed by replacement of the perthites. The presence of accessory minerals like fluorite, pyrochlore and astrophyllite may well be associated with the late stage hydrothermal albitisation. In other localities in this province allanite has been reported while biotite has been found as an accessory as well as a major constituent in the albite-riebeckitic-arfvedsonite granites (Borley, 1963; Turner, 1962; Bowden and Turner, 1974). At Kigom Hills in this same province, ore minerals including molybdenite, pyrite and chalcopyrite have been reported in this rock type (Borley; 1963).

Other Minor Rock Types

The other rock types at Dutsen Wai are minor and can only

be observed as evidence of the typical complete magmatic cycle that is common to all the Younger Granite complexes in this province.

Dolerite dyke

The dolerite dyke, which is about 2 cm wide is believed to be a late basic dyke and contains minerals which are similar to the basaltic late dolerite dykes at Gindi Akwati. In thin section, it is very fine grained and contains prismatic plagioclase in groundmass which is composed of chlorite, calcite and quartz. Epidote occurs in clusters and minute aggregates, while a few stains of iron oxides are also present.

Agglomerates

The agglomerates are derived mainly from fracture of pre-existing Basement rocks and only a few of the pyroclastic materials can be referred to as volcanic breccias.

Crushed breccia

The crushed breccia was examined in thin section but due to the intense weathering and alteration, it is not possible to ascertain its parent rock. The rock is generally dark grey possibly due to clay minerals that have formed after alteration. Brown gels of iron oxides are abundant and it appears the rock has undergone some recrystallisation as small quartz veins are present. This brecciated rock could be due to volcanic activity after faulting but because of the absence of any volcanic breccias or agglomerates in the vicinity, it is best interpreted as a fault zone which has produced the valley that drains the complex. It appears there has been a slight displacement of the northern portion of the biotite granite to the north-west relative to the southern portion.

The Dutsen Wai intrusion is believed by the writer to

have formed as a small ring complex and in order to show the close resemblance with typical ring complexes in this province, one of such complexes is described and compared with Dutsen Wai.

Turner (1963) has described the Sara-Fier complex and established the order of events which is typical of the complexes in this province. At Sara-Fier the order of events was:-

(1) Intrusion of early volcanic rocks, mainly rhyolites.

(2) ring-fracture, cauldron subsidence and the intrusion of a ring dyke often of hornblende-granite-porphyry or hornblende-pyroxene-fayalite-granite.

(3) The emplacement of a succession of granites within this ring fault, generally in a concentric fashion and including hornblende-biotite, biotite and riebeckitic-arfvedsonite granites.

At Dutsen Wai large occurrences of such rocks are not present but this could be due to erosion of most of the earlier formed rocks. However the following evidence is still represented:-

(1) Early volcanic rocks are preserved in the form of agglomerates and volcanic breccias.

(2) There is a fault zone represented by the NW-SE trending valley along which exists a crushed breccia.

(3) A granite porphyry dyke has been observed in one of the tin workings.

(4) A late dolerite dyke occurs within a basement outcrop.

(5) Two granite phases; the albite-riebeckitic-arfvedsonite and biotite granites are present.

These events may have occurred as at Sara-Fier but only on a smaller scale and further erosion may have reduced

the Dutsen Wai complex to its present condition.

4.2. Geochemistry

Two samples each of the biotite and the riebeckitic-arfvedsonite granites were analysed for both major and trace elements. Although the samples analysed are too few to draw general conclusions, certain typical trends can be observed. Considering only the normative salic minerals, Bowden and Turner (1974) found that these plutonic acid rocks are a closely unified group of hypersolvus alkali granites. The only exceptions are the albitised varieties of these rocks which deviate from this trend, and this has been explained as being due to the effects of hydrothermal modification.

Major Element Chemistry

The analysed samples (Table 4.6) show little variation in most of the major elements. The riebeckitic-arfvedsonite granite shows lower silica (SiO_2) and alumina (Al_2O_3) over the biotite granite, while values of total iron (Fe_2O_3 + FeO) and soda (Na_2O) are higher than these of the biotite granite. The results of the analysis for major elements are presented (Table 4.6) together with similar rocks elsewhere in the same province.

Variation diagrams have been used to plot the major element constituents as oxides against silica (SiO_2) content (Fig. 4.2a-f).

From the results and oxide variation diagrams the following characteristics can be observed:-

1. It appears that as the silica content increases in the riebeckitic-arfvedsonite granite, the alumina content decreases. It is not obvious what is happening in case

Fig 4-2 Oxide variation diagrams
▲ riebeckitic-arfvedsonite granite
● biotite granite

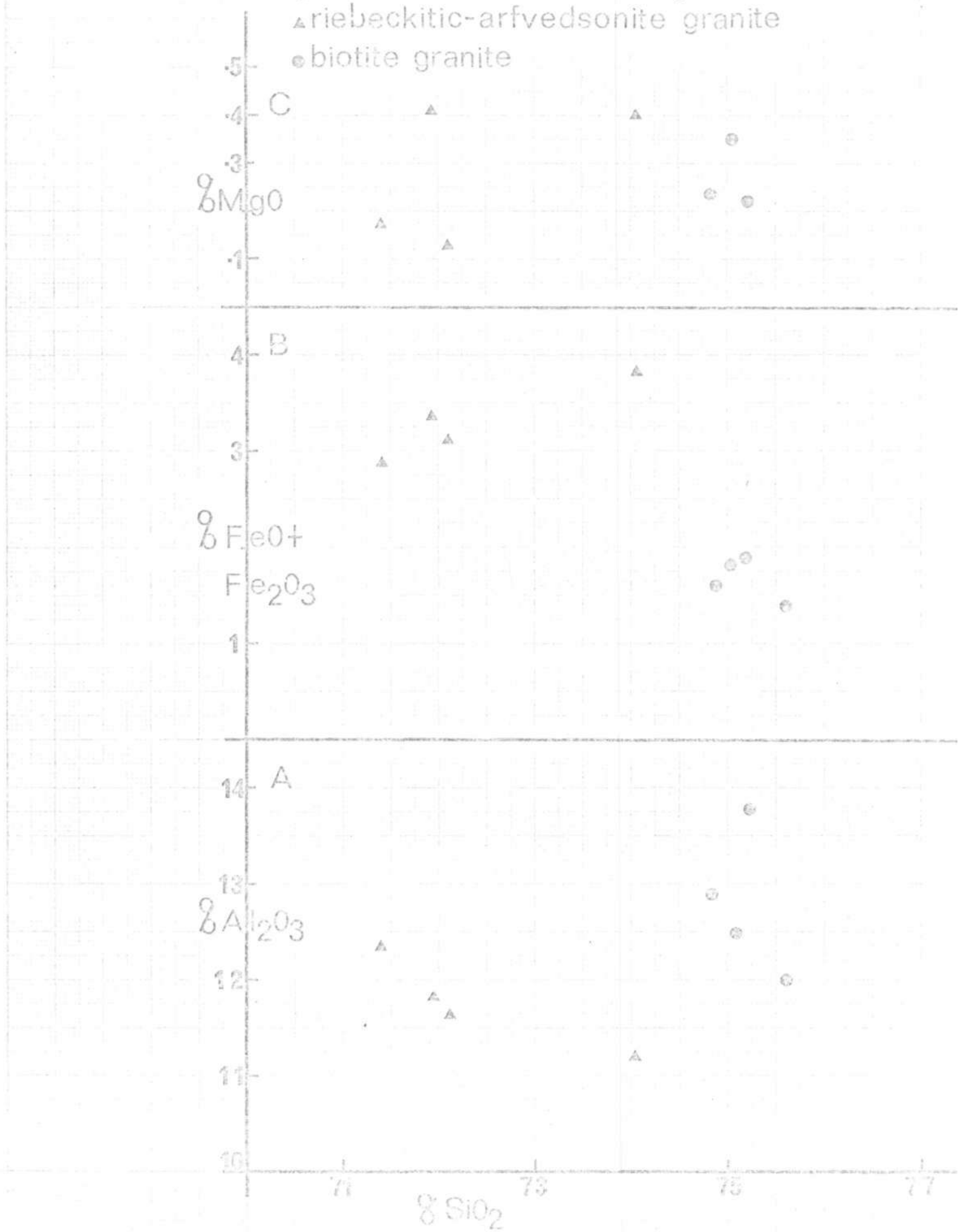


Fig4-2 Oxide variation diagrams

▲riebeckitic-arfvedsonite granite

●biotite granite

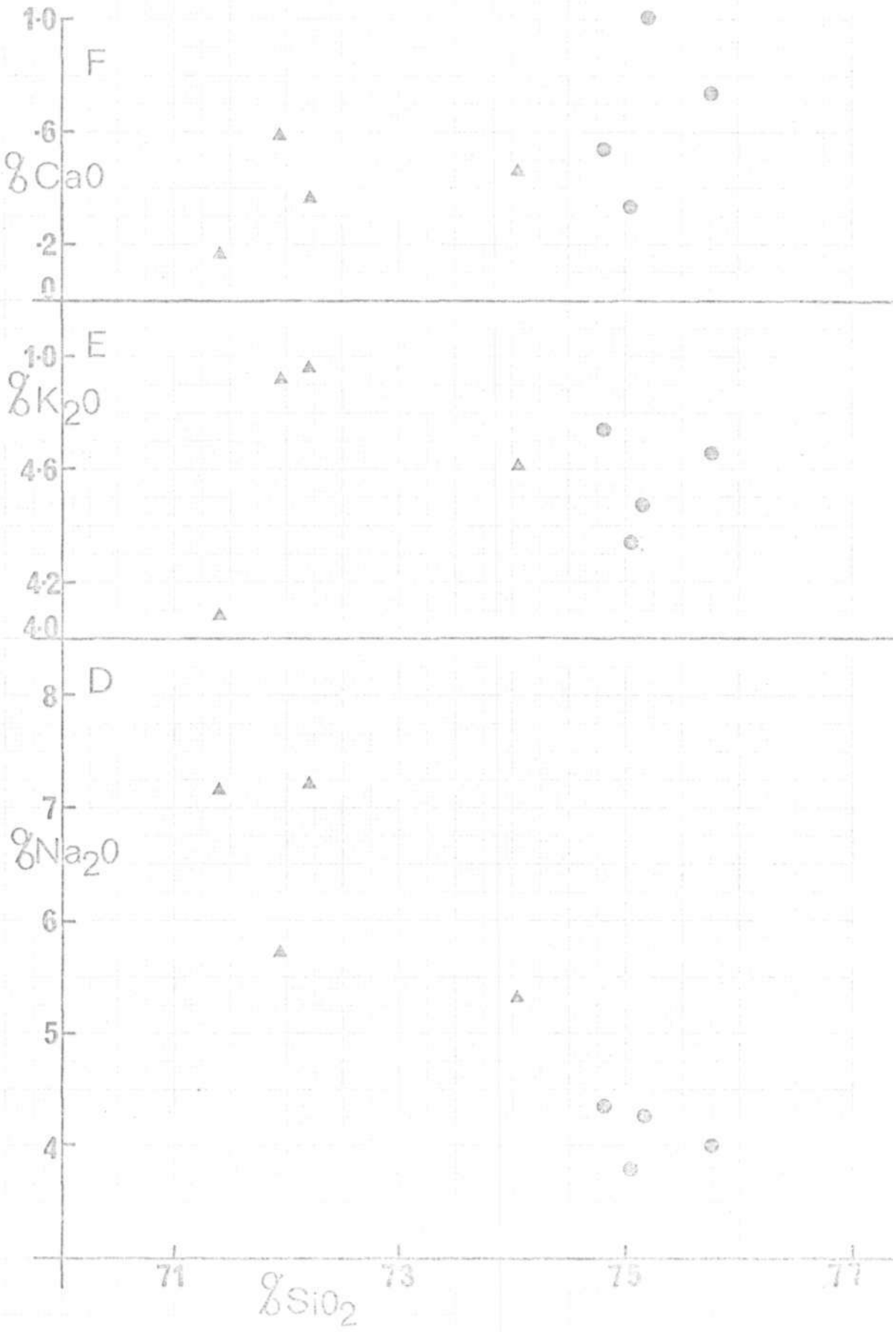


Table 4.6. Chemical analysis of Biotite and Riebeckitic-arfvedsonite granites.

	DW 7	DW 16	5	6	DW 11	DW 13	7	8
SiO_2	75.18	74.83	75.10	75.77	72.17	71.95	71.38	74.05
TiO_2	0.10	0.12	0.47	0.07	0.19	0.27	0.07	0.35
Al_2O_3	13.79	12.93	12.47	12.03	11.61	11.83	12.34	11.20
Fe_2O_3	0.78	0.69	0.47	0.31	1.88	1.68	1.96	2.10
FeO	1.09	1.10	1.35	1.07	1.23	1.70	0.91	1.70
MnO	0.03	0.04	m il	0.02	0.06	0.09	0.05	0.10
MgO	0.21	0.22	0.35	trace	0.14	0.41	0.16	0.40
CaO	0.34	0.64	1.00	0.72	0.36	0.39	0.17	0.45
Na_2O	4.26	4.35	3.75	4.08	7.23	5.74	7.17	4.60
K_2O	4.33	4.74	4.46	4.65	4.97	4.93	4.17	5.20
P_2O_5	0.04	0.06	0.03	0.03	0.03	0.06	0.01	0.06
H_2O^+	0.26	0.34	0.35	0.16	0.59	0.71	0.30	0.42
H_2O^-	0.23	0.16	0.25	0.14	0.11	0.20	0.12	0.10
F	0.26	0.88	0.09	0.11	0.45	1.73	1.08	n.d.
Sub	100.90	101.10	100.14	99.74	101.02	100.98	100.53	100.73
Less O	0.15	0.18	0.04	0.04	0.43	0.61	.48	
Total	100.75	100.92	100.10	99.70	100.59	100.37	100.05	100.73
Quartz	30.40	27.25			24.27			
Or	23.75	26.37			27.58			
Ab	37.67	38.24			32.63			
An	1.06	1.73			-			
Actinolite	-	0.88			1.34			
Riebeckite	-	-			4.80			
Biotite	2.33	1.69			0.95			
Corundum	1.83	-			-			
Sphene	0.21	0.25			0.38			
Magnetite	0.80	0.71			-			
Apatite	0.08	0.12			0.06			

DW 7 and DW 16.	Biotite granites, Dutsen Wai (Analyst - S.I. Abaa, 1976).
DW 11 and DW 13.	Albite-riebeckitic-arfvedsonite granites, Dutsen Wai. Analyst S.I. Abaa
No. 5.	Biotite granite Kudaru (KD 165) taken from MacLeod et al. (1971) P. 64.
No. 6.	Biotite Granite, Rep. B 850 taken from Jacobson et al. (1958) P. 14.
No. 7 and 8.	taken from Bowden and Turner (1974) P. 340.

of the biotite granite. However Weir (1974) found in the Rop complex that as the silica content of the biotite granite increased the alumina content also increased. If both the riebeckitic-arfvedsonite and the biotite granites are considered together here, then there is a distinct increase in alumina as the silica content of the rocks increases.

2. Considering the total iron (Fe_2O_3 + FeO) in the riebeckitic-arfvedsonite granite, it appears that as the silica content increases, the total iron content also increases. The reverse is the case in the biotite granite, however, if both rock types are considered, there is a decrease in the iron content as the silica increases. This is the same case with the biotite granite from Ririwai as reported in Chapter Two.
3. Both rocks show a decrease in their magnesia (MgO) content as the silica content increases.
4. Soda (Na_2O) distinctly decreases as the silica content increases. The values are highest in the riebeckitic-arfvedsonite granite where the silica content is lowest.
5. Potash (K_2O) remains relatively constant in both rock types.
6. Lime (CaO) is generally low in the rocks but shows a slight decrease with increasing silica.

The lime and magnesia content of these rocks are consistently low and the low lime content is reflected in the nature of the plagioclase which rarely contains more than 5 percent anorthite. The low magnesia is reflected in the type of the ferric minerals; riebeckitic-arfvedsonite in the per-alkaline rock and the iron rich mica in the biotite granite. Bowden and Turner (1974) found that despite the alkaline nature of this granite province, the Na and K values are not particularly

high, and only the albite-rich peralkaline granites have a significantly high Na concentration. In the analysed samples, the albite-riebeckitic-arfvedsonite granite contains more modal albite than the biotite granite. Similarly, in the chemical analysis the albite-riebeckitic-arfvedsonite granite contains the highest value of soda (7.23 percent Na_2O) compared to the highest value of 4.35 percent Na_2O in the biotite granite. Bowden and Turner (1974) concluded that the peralkaline character of this Younger Granite province is due to a deficiency of alumina relative to soda and potash. The increase in iron (Fe_2O_3 + FeO) in the riebeckitic-arfvedsonite granite over the biotite granite can be attributed to the appearance of riebeckitic-arfvedsonite which is rich in iron (Fe^{3+} + Fe^{2+}) and aegirine which is also rich in iron (Fe^{3+}). The alkali amphiboles of this rock have high iron content, low alumina, lime, magnesia but relatively high values of soda and potash (Table 4.7).

The alkali and alumina contents of these rocks have given rise to their classification based on their agpaitic ratios. This ratio is based on the molecular proportions of potash (K_2O), soda (Na_2O) and alumina (Al_2O_3) where the agpaitic ratio =

$$\frac{\text{M.P. } (K_2O) + \text{M.P. } (Na_2O)}{\text{M.P. } (Al_2O_3)}$$

where M.P. = molecular proportions.

This ratio is indicative of the prevailing alkali conditions at the time of crystallisation (Bowden and Van Breemen, 1970; Sørensen, 1974). The agpaitic granites have a ratio greater than unity, and their characteristic minerals are aegirine and riebeckitic-arfvedsonite. Those with the ratio less than unity

are termed plumasitic (Bowden and Van Breemen; 1970) or miaskitic (Sørensen; 1974), and are usually characterised by biotite, hornblende and pyroxene.

The analysed samples from Dutsen Wai fall into these two groups; the two samples DW 11 and DW 13 (Table 4.6) have ratios of 1.49 and 1.25 respectively and are agpaitic since they also contain both aegirine and riebeckitic-arfvedsonite. The samples DW 7 and DW 16 (Table 4.6) have ratios of 0.88 and 0.95 respectively and are therefore plumasitic, confirmed by their content of biotite as a characteristic. These rocks therefore fall in the two groups of rocks from this province termed peralkaline for the agpaitic group and non-peralkaline for the plumasitic type (Bowden and Van Breemen, 1970; Bowden and Turner, 1974; Bowden 1974 and 1975; Weir, 1974).

Trace Element Chemistry

Some trace elements were analysed for in the two types of granites, and the results are presented (Table 4.8).

Lithium (Li)

Li concentrated in both rocks, but the amount in the albite-riebeckitic-arfvedsonite granite is about four times the amount in the biotite granite. This can be attributed to the minerals aegirine, riebeckitic-arfvedsonite and astrophyllite which are rich in the ions Fe^{2+}, Fe^{3+} and Al^{3+}, and Li substitutes chiefly for them. The lower values for Li in the biotite granite could be due to low concentration of Li in feldspars which are the major minerals in the biotite granite. However the available Li in the biotite granite can be attributed to the biotites of the granite which can contain Li. Rb also concentrated well in both rocks and Bowden (1966a) stated that both Li and Rb exhibit a dual role of concentrating in both

Table 4.7. Chemical Composition of Alkali Amphiboles.

	1	2	3	4
SiO_2	50.25	49.15	49.61	48.83
ZrO_2	0.56	0.20	0.21	0.31
Al_2O_3	0.26	0.95	0.27	2.31
TiO_2	0.80	1.14	0.52	1.12
Fe_2O_3	13.95	13.10	12.91	10.90
FeO	17.09	20.60	19.50	21.77
Li_2O	2.20	1.16	1.76	n.d.
MnO	0.62	0.32	0.48	0.27
MgO	0.04	0.30	0.13	0.06
ZnO	0.93	0.64	0.47	n.d.
PbO	0.18	0.04	0.07	n.d.
CaO	0.20	0.64	0.31	1.32
Na_2O	8.80	7.66	9.43	8.75
K_2O	2.20	1.96	1.65	1.22
P_2O_5	0.16	0.04	0.13	trace
H_2O^+	0.40	1.30	1.10	1.47
H_2O^-	0.09	0.10	nil	0.28
F	3.31	2.17	2.48	2.30
Cl	0.18	0.16	0.09	n.d.
	102.32	101.63	101.12	100.94
Less O = F, Cl	1.43	0.96	1.06	0.97
Total	100.79	100.67	100.06	99.97

1. Amphibole, from albite-riebeckite granite P.B. 3 Kaffo Valley, Liruei Complex taken from Borley (1963) P. 367.
2. Riebeckite, from riebeckite-aegirine-granite, Kigom (P.B. 85), taken from MacLeod et al. (1971) P. 72.
3. Riebeckite, from albite-riebeckite-granite, Amo (L 994), taken from MacLeod et al. (1971) P. 72.
4. Riebeckite, from riebeckite-granite, Kudari, taken from Jacobson et al. (1958) P. 18.

Table 4.8. Some Trace Element Data: Dutsen Wai Granites.

Element in p.p.m.	DW 7	DW 16	DW 11	DW 13
Rb	413	438	1151	739
Sr	0	0	38	7
Y	84	81	137	1112
Zr	145	153	184	1287
Li	190	265	885	595
Be	5	12	28	26
Ni	10	10	10	10
Sn	10	10	50	30
Cu	11	10	17	8
Pb	29	11	34	105
Zn	107	57	624	485
U	11	65	132	111
Th	19	23	38	69

DW 7 and DW 16. Medium grained biotite granite, Dutsen Wai.

DW 11 Albite-riebeckitic-arfvedsonite-granite, Dutsen Wai.

DW 13 Albite-riebeckitic-arfvedsonite-aegirine granite, Dutsen Wai.

Analysts:

U and Th:- S.I. Abaa.

Pb, Zn, Cu, Li, Be, Ni and Sn:- R. Batchelor.

Rb, Sr, Y and Zr:- E. Cox.

er lka ine and non-peralkali e gra ites.

Be and Ni

Be and Ni show low values in both rocks. Ni is less than 10 ppm in both rocks while Be shows a maximum of 12 ppm in the biotite granite but up to 28 ppm in the peralkaline rock. Be values in Calc- alkaline granites of this province have a common range of between 1 and 3 ppm and there is a general but overall increase in Be from early to late formed rocks, culminating in the albite-riebeckitic-arfvedsonite granites. However these rocks can be said to be enriched in the two elements since average abundances of the elements in granites is 5 ppm Be and 0.5 ppm Ni (Krauskopf; 1967).

Zn.

Zn values are much lower in the biotite granite where from the analysed samples they range from 57-107 ppm, while the values increase in the riebeckitic-arfvedsonite granite, ranging from 485-624 ppm. Elsewhere, the Younger Granites of this province contain 200-300 ppm Zn, this value rising to 828 ppm in biotite granite (Table 2.5) while MacLeod *et al*. (1971) have stated that this value may rise to 1,000 ppm in the albite-riebeckitic-arfvedsonite granites. From table 4.7 it can be seen that Zn is contained preferentially in the amphiboles especially the riebeckitic-arfvedsonites, but is low in the biotites (Table 2.3). Fuge (1974) has reported a mean value of 39 ppm and a range of 12.5-60 ppm in granites from S.W. England, while Krauskopf (1967) has stated that the average abundance of Zn in granites is 40 ppm. In this regard we can conclude that these granites are enriched in Zn.

Cu

The biotite granite contains 10 and 11 ppm Cu while the riebeckitic-arfvedsonite granite contains 8 and 17 ppm Cu, while the average abundance of Cu in granites is 10 ppm which

implies hat these rocks are neither depleted nor enriched in Cu.

Pb

Pb is more concentrated in the peralkaline granite with a mean value of 67 ppm while the biotite granite contains a mean value of 20 ppm. The average abundance of Pb in granites is 20 ppm (Krauskopf; 1967) which agrees well with the value found in the biotite granite, but in the peralkaline granite Pb is enriched. This can be attributed to the late hydrothermal fluids that induced albitisation in the peralkaline rock as well as substitution in the lattices of the amphiboles (Table 4.7).

Sn

The biotite granite contains an average of 10 ppm Sn while the peralkaline granite contains an average of 40 ppm Sn. The average content of Sn in granites is 3 ppm (Krauskopf; 1967) which means that both granites here are slightly enriched in Sn. In the biotite granite, Sn can be carried in the biotites while in the riebeckitic-arfvedsonite granite, small amounts may have been introduced by late hydrothermal fluids that induced recrystallisation in the rock.

Sr

The biotite granite here has shown zero values for Sr while the peralkaline granite contains an average of 22 ppm. It is possible that Sr was not detected by the method of analysis in the biotite granite, however Bowden and Jones (1975) and Bowden and Van Breemen (1970) have also found similar results in similar rocks from this province. Krauskopf (1967) has given an average of 285 ppm in granites which means that if there is no error of analysis, then the granites of this province have been highly depleted in Sr.

Rb

Rb values range from 739-1151 ppm in the peralkaline granite, while in the biotite granite, they range from 413-438 ppm. The average Rb content of granites is 150 ppm which means that these granites are enriched in Rb. The Rb contents of the Younger Granites of this province have been discussed (Butler et al. 1962) including the ratio of K to Rb. The authors found that generally, the Rb content increases, and the K/Rb ratio decreases from the hornblende-fayalite-granites through the hornblende-biotite granites to the biotite and riebeckitic-arfvedsonite granites recording the highest value of 1,400 ppm Rb in an albite-riebeckitic-arfvedsonite granite.

Zr

Zr values in the two granites were variable. The biotite granite has lower values, (145 and 153 ppm) than the peralkaline granite which has values of 184 and 1287 ppm. In thin section, zircon was observed to be more abundant in the peralkaline granite with a maximum modal value of 0.2 percent in sample DW 13, compared to a maximum value of 0.1 percent in the biotite granite. Besides, the amphiboles also contain up to 0.56 percent ZrO_2 (Table 4.7). These factors could have contributed to the enrichment of Zr in the rock. In his study of Zr in the Younger Granites of this province, Bowden (1961) showed the existence of two distinct evolutionary trends. The first is marked by a progressive decrease in Zr from the early hornblende-fayalite granite through hornblende-biotite granites to biotite granites. This trend is reflected in the early precipitation of early formed euhedral zircons which are large and abundant in the hornblende-fayalite granites, but inconspicuous in the biotite granites. The second trend is in the alkaline rocks and shows high Zr values for the arfvedsonite-

fayalite granites, increasi g into the rie eckitic-aegirine granites and reaching a maximum in the albite-riebeckitic-arfvedsonite granites.

This maximum has also been obtained in the albite-riebeckitic-arfvedsonite granite at Dutsen Wai quite in agreement with Bowden's findings. Bowden (1961) regarded this trend as a reflection of the increasing solubility of Zr in the alkaline magma in agreement with similar rock series elsewhere (Butler and Smith; 1962).

Fluorine

Fluorite occurs in both rock types and the total amount of fluorine obtained in the analysis could be from fluorite as well as from other minerals such as biotite in the biotite granite and from amphiboles in the peralkaline granite. Although fluorite is a conspicuous accessory mineral in the biotite granite, much of the F is present in other minerals and there is little correlation between F rich samples and these high in lime. In the riebeckitic-arfvedsonite granite, cryolite and riebeckitic-arfvedsonite are significant F bearing minerals and the minerals could contain as high as 3.31 percent F (Table 4.7).

U

The uranium values for the two rock types vary, with the biotite granite containing 57 and 107 ppm U while the albite-riebeckitic granite contains 485 and 624 ppm U. Both rocks show enrichment in U since the average U content of granites is 4.8 ppm (Krauskopf; ,1967). The high values obtained in the peralkaline granite are reflected in the uranium bearing minerals that are present in the rock. Pyrochlore occurs in the peralkaline rock together with cryolite and they appear in the modal analysis of the rock

Th

Thorium values range from 19-23 ppm in the biotite granite and 38-69 in the peralkaline granite. Both rocks are enriched in Th compared to an average value of 17 ppm in granites although in case of the biotite granite it is justifying to conclude that it neither depleted nor enriched. The enrichment in the riebeckitic-arfvedsonite granite is also small compared to other similar rocks in this province.

It has been found that in general there is a concomitant rise in Th and U in the albitised peralkaline granites (Bowden et al., 1975), while Uranium behaves in a similar way to Zr (Bowden; 1966b) and its geochemical behaviour is closely related to the peralkalinity and albitisation. From the modal analysis of the two rock types here, it can be seen that the peralkaline granite contains more uranium bearing minerals than the biotite granite. Thorite and orangite have been reported in the biotite and peralkaline granites of this province (Jacobson et al., 1958), and both the pyrochlore from the albite-riebeckitic-arfvedsonite granites and the fergusonite from the alkali-amphibole granites are uraniferous. It has also been found that the pyrochlore from Kaffo Valley - Ririwai, contains up to 3.5 percent urania and 4.3 percent thoria (Beer; 1952) while the fergusonite from Jarawa contains 3.5 percent thoria and 1.7 percent urania.

The results of the analyses of the Dutsen Wai granites compare very well with results of similar rocks elsewhere in this Younger Granite Province (Bowden and Turner; 1974; Weir, 1974; Butler and Thompson, 1964; Butler and Smith, 1962). From these results certain trends have been observed. Elements have distinctly shown increased concentration from the biotite granite to the peralkaline granite. Perhaps the main reason is

the late hydrothermal fluid action which caused albitisation in the peralkaline granite that was responsible for the trace element enrichment. Besides, the trace elements have a greater tendency for substitution in the minerals contained in the peralkaline granite than in the biotite granite. The albitisation stage was also responsible for introduction of minerals like pyrochlore, cryolite amblygomite and astrophyllite in the peralkaline granite. It can be said that the albite-riebeckitic-arfvedsonite granite at Dutsen Wai is mineralised although the mineralisation is a dispersed type.

The concentration of elements in a liquid depends on the partition coefficient for the elements, between the liquid and any solid phases with which the liquid is in equilibrium. This would be either during separation from its source or during subsequent fractional crystallisation. The activity coefficients will not vary greatly within the solid phase, but will vary greatly with other factors such as the acid/base strength of the melt, the ionic potential of the melt and the effect of volatiles (Allegre and Michard; 1973). These factors must have controlled the fractionation of trace elements in the two rock types analysed. The samples show enrichment in Rb, Zr, Li, U and Th and a marked depletion in Sr especially in the biotite granite. Other trends are the decrease of Zr in the biotite granite, increasing Li in the peralkaline granite and increasing Zn in the same granite type. The tendency observed is therefore that, the trace elements showed some affinity to the more fractionated and alkaline liquids, although this is less marked in the case of Rb. Zr levels in the rocks are higher in the peralkaline types and they mark the variation in the agpaitic ratios, but Bowden and Turner (1974) have suggested that the hydrothermal development of albite may have been responsible for the upgrading of not

only Rb, but also Nb, Sn and U. Furthermore, Bowden (1975) found a marked elevation in the $^{87}Sr/^{86}Sr$ initial ratio for all medium grained plumasitic biotite granites with late magmatic apogranitic characteristics containing dispersed columbite, thorite and xenotime. This elemental enrichment must have been part of the late fluid action on these rocks.

Mineralisation

At Dutsen Wai, tin mineralisation has been observed only in the alluvials together with columbite. At present not much mining goes on here since there is virtually none of these minerals left for commercial exploitation. A little pitting by the local people however still goes on although sometimes nothing is got from the workings (by discussion with one of the persons I met digging around for tin). The little alluvial tin is found in the vicinity of the intrusion particularly along the valley that has dissected the intrusion. Wolfram had been won in this area outside the granite contact (Haag; 1943). Haag also reported a vein in the basement gneiss about 1½ km from the intrusion, but it contained only wolfram as an economic ore. He further stated; "there are no veins within the contact, and the intrusion has reached the denuded stage, there is abundant cassiterite in the alluvials, almost to the middle of the granite outcrop".

The absence of veins, lodes and greisens at Dutsen Wai suggests that cassiterite and columbite must have been disseminated in the granite as accessory minerals and may also have been contained in other minerals such as biotite. It is possible that on weathering of the granite, the elemental tin (Sn) may have separated from the minerals and due to oxidation, formed cassiterite which is found in the alluvials. Such cassiterite

formation is possible if the concentration of the anion O^{2-}, the redox potential and the pH conditions of the environment are such that the higher valence oxides and hydroxides of Sn would not go into solution. This is possible for Sn^{4+} due to the insolubility of its oxides and hydroxides. If the hydroxide of Sn^{4} is formed, or even lower valence oxides or hydroxides of Sn are formed then under acid conditions they could be oxidised to the higher valence Sn forming cassiterite which is the most stable state. Krauskopf (1967) has stated that tin also commonly remains in the oxidised zone as an oxide of higher valence (SnO_2, cassiterite), either residual from the ore or formed by oxidation of other tin minerals.

Alternatively, cassiterite at Dutsen Wai may have been in the rock only in the very limited roof zones and these zones having been completely weathered after exposure, concentrated cassiterite in the alluvials and left the remaining intrusion virtually barren of tin. This is likely since no cassiterite was observed in the thin sections examined. But chemical analyses gave Sn values ranging from 10 ppm in the biotite granite to 50 ppm in the peralkaline granite.

The concept of Sn in individual minerals has been strengthened by the work of Bradshaw (1967) who measured the content of Sn and other trace elements in feldspars, biotites and muscovites from British granites (Cornwall) in relation to mineralisation. He found that feldspars, biotites and muscovites from unmineralised granites contained 15 ppm, 11 ppm and 28 ppm Sn respectively, while in the mineralised granites the values were 29 ppm, 44 ppm and 52 ppm respectively. Jedwab (1955) working on granites reported that feldspars, biotites and

muscovites from unmineralised granites contained 5 ppm 67 ppm and 71 ppm Sn respectively while in the mineralised granites the values were 16-32 ppm Sn in feldspars, 110 ppm Sn in biotites and 120 ppm Sn in muscovites. Hesp (1971) found that in a wide range of unmineralised granites in Australia, biotites carry up to 45 percent of the total tin content of the granite.

Mineralisation at Dutsen Wai may have been in two forms. One in the biotite granite where during the limited introduction of albite at the time of cooling in the roof zone, columbite, thorite and other minerals including probably cassiterite were dispersed throughout the roof zone. Weathering of the roof zones since Mid-Tertiary times may have produced tin rich and columbite alluvials. The second form of mineralisation would be found only in the peralkaline granite, where albitisation introduced an enriched range of trace elements with abundant albite, uraniferous pyrochlore and induced considerable recrystallisation. In general there is no more economic mineralisation at Dutsen Wai for exploitation, however more work will be needed to assess the extent of mineralisation of the albite-riebeckitic-arfvedsonite granite with pyrochlore, astrophyllite, cryolite and amblygonite.

CHAPTER 5

Origin and Comparison of the three areas.

All the three areas studied occur in a single petrographic and metallogenic province, but there are slight differences in the environment or host rocks containing the major lodes and ore minerals. However the source of the ore mineralisation and the processes of deposition are virtually all the same. The Nigerian Younger Granite Province in which the mineralisation occurs has many rock types usually occurring together as ring complexes. The main differences in the various rock types are textural, mineralogical and chemical compositions, with their magmatic source believed to be the same.

Origin of the Younger Granites

The Younger Granites have been studied by many workers to explain their origin. The main rock type associated with the mineralisation is the biotite granite, but in all cases the biotite granites occur associated with other rock types, particularly the peralkaline granites.

Black (1958) showed that biotite granite can be derived from hornblende-fayalite granite by the removal of early formed alkali feldspars, fayalite and pyroxene at high temperatures, while the early crystallisation of hornblende from the magma at low temperatures could produce a riebeckitic-arfvedsonite granite. However this proposal has not taken account of the high agpaitic ratios found in the riebeckitic-arfvedsonite-granites, and Turner (1971) observed that in the series hornblende-fayalite granite to hornblende-biotite granite to biotite granite, there is a good deal of evidence in favour of a crystal differentiation mechanism, but the subtraction of the maximum possible amount of

hornblende from the hornblende-fayalite granite would bring about a greater impoverishment in Fe and Ca than is observed in these rocks. Marmo (1965) suggested that the different rock types were formed as a result of local circumstances during intrusion, whereby each produced material different from the previous one. The prevailing circumstances have not been specified, but it would seem that this may not have been the case, since individual complexes follow a definite trend of intrusion as well as comparative volume of each type of rock with one another.

By studying the system Na_2O-Al_2O_3-Fe_2O_3-SiO_2 at 1 atm., Bailey and Schairer (1966) suggested a peralkaline magma, since pantellerites show the existence of a eutectic similar to their experimental one with a quartz-albite-acmite-Na-disilicate liquid. If the peralkaline granites were erupted into the crust with such a composition, they would survive and be intruded by a feeder arrangement. This too has not been substantiated to be the case with the Nigerian Younger Granites. The peralkaline granites have been observed in field but such intrusion through a feeder arrangement has not been observed in any form. Tugarinov (1965) studied the isotopic composition of lead in galena from Older Granites, Younger Granites, and Cretaceous sediments from Nigeria and concluded that the origin of the Younger Granites was by a complete refusion of crustal material rich in Pb, U and Th, and this caused the change in the lead composition from the Older Granites compared with the Younger Granites. This theory seems to agree with Freeth (1970) who suggested that the Younger Granites were produced by partial melting of the crust, followed by high level fractionation.

On investigating the associated basalts and rhyolites, Yoder (1973) proposed that fractional melting producing two magmas of varying composition is possible from the same parent material. Melting would be possible by adiabatic decompression, producing separate magmas at different points over a long period, and if hydrous minerals are retained in the parent material during formation of both magmas, rhyolites and andesites would be produced, but if the water of the parent material were used up at the initial stage of fractional melting, then rhyolites and tholeiites would form. Even if this had happened in this province it must have been the rhyolites and andesites process only and would not explain the origin for all the complexes since andesites are not present in most of the complexes, and the second process is absent since no tholeiites have been reported in this province.

Other workers suggest that plate tectonics may have produced the Nigerian Younger Granite province. Bailey (1964) compared the province with East Africa because of the basin and swell structures and by the fact that the province is on an uparched area. Rhodes (1971) suggested an extension of the fractures separating the African and South American plates, while Morgan (1971) suggested a hot spot at Ascension Island.

Bowden (1970) used the similarity of lead isotopic composition in Older Granites, pegmatites and the Younger Granites as well as the distribution of tin and the absence of tourmaline in the ring complexes to establish that the Younger Granites were derived from an initial peralkaline melt by fusion of local basement rocks. He further suggested that the associated metaluminous trend is caused by more complete melting, while the peraluminous granites developed during

subsequent cooling. Further partial melting experiments on Nigerian charnockitic monzonite, associated with migmatised gneisses produced liquids from which the metaluminous Younger Granites could be derived (Brown and Bowden, 1973). The experiments further showed that on cooling towards the Granite system minimum, the liquids could evolve into metaluminous hastingsite-biotite granite and peraluminous biotite granite. They however found that partial melting of charnockitic monzonites could not yield peralkaline liquids at 750-850°C, and that syenitic rocks of this province may either reflect the action of late stage albitising fluids on residual charnockitic material after partial melt extraction, or the collection of feldspar, floated from a hastingsite-fayalite granite liquid.

With the chemical and mineralogical composition of the two rock types studied here, it can be concluded that whatever the starting material was, the granites in this province formed by differentiation. These rocks show trends of two distinct processes of differentiation producing varying series. The main series are the hornblende-fayalite-granite to hornblende-biotite granite to biotite granite, and hornblende-fayalite-granite to arfvedsonite-fayalite granite to riebeckitic-arfvedsonite-granite. Turner (1971) stated that the early crystallisation and removal of mafic minerals, would produce the hornblende-fayalite-granite to hornblende-biotite granite to biotite granite, termed a 'normal series' while the initial precipitation of plagioclase would produce the hornblende-fayalite-granite to arfvedsonite-fayalite granite to riebeckitic arfvedsonite granite series, termed 'alkali series'. These fractionation trends have produced the biotite and the

riebeckitic-arfvedsonite granites which are associated with mineralisation, although the biotite granites are the most important source of mineralisation.

The riebeckitic-arfvedsonite granites show late crystallisation of the mafic minerals; aegirine and riebeckitic-arfvedsonite, which would allow many minor and volatile components to remain dissolved in the magma and partly taken into the lattices of the late crystallising mafic minerals. This is confirmed by the high content of F, cl, Li and H_2O in the amphiboles (Table 4.7). It is obvious that the last crystallising fluids will contain dissolved volatiles, ions that were not taken in by already crystallised minerals and possibly silica and water. These residual fluids will increasingly be enriched in volatiles as crystallisation continues, and their compositions will continue to change. Kovalenko (1968) remarked that as temperature drops and further crystallisation occurs residual fluids become increasingly enriched in volatiles, changing continuously without supercritical phenomena, from a magma with an agpaitic composition to a sodium-silicate rich hydrothermal solution. Perhaps in the riebeckitic-arfvedsonite granites, the action of such residual fluids on the early crystallised minerals would change their composition. The action of such a residual sodium-silicate rich hydrothermal solution is also responsible for the introduction of late albite, microcline and quartz as well as the diffuse mineralisation observed in the Nigerian rocks. This albitisation of the rocks introduced an enriched range of trace elements, abundant albite, uraniferous pyrochlore, cryolite, amblygonite and astrophyllite (Tables 4.3 and 4.8) and induced considerable recrystallisation as seen at Dutsen Wai.

In the biotite granites, the early crystallisation of mafic minerals would reduce the amount of volatiles that would be taken in by any more crystallising minerals. As crystallisation continues, the concentration of volatile components will increase in the residual sections until saturation, and an aqueous phase will separate. The fluid phases with dissolved ions will then invade the crystalline granite roof zones resulting in the transformation of biotite into micas as well as the formation of lodes, veins and greisens as seen at Ririwai.

The above two differentiation processes have been well illustrated by zircon (Turner, 1971). In the biotite granite series, zircon shows a progressive decrease due to the early crystallisation and removal of zircon, but in the riebeckitic-arfvedsonite granite series, zircon shows a progressive increase due to its increasing solubility in the alkaline magma, producing a strong contrast in the end members; the biotite granites and the riebeckitic-arfvedsonite granites. From Dutsen Wai the trace element analysis gives Zr values of 184 and 128⅝ ppm in the albite-riebeckitic-arfvedsonite granite while in biotite granite the values are 145 and 153 ppm. Similarly in the modal analysis the albite-riebeckitic-arfvedsonite granite contains a maximum of 0.2 percent zircon while the biotite granite contains a maximum of 0.1 percent zircon.

Comparison of the three areas studied.

In the areas studied, the fractionation trends discussed above have been recorded, and at least one phase of mineralisation as discussed above is recorded. At Gindi Akwati, both the peralkaline and the biotite granites are not found in the immediate vicinity of the mineralised zone, however both phases

are present in the ring complex in which the mineralisation occurs. Besides, there is strong evidence to suggest that there may be a biotite granite in the vicinity at greater depths. A comparison of the three areas is presented as a summary in Table 5.1.

History of the three areas.

In the past, both areas have been very productive in columbite and cassiterite. Rop complex in which Gindi Akwati occurs is the second largest tin producer in the Nigerian Younger province, and alluvial cassiterite has been exploited for over 50 years (Black; 1971). The Gindi Akwati lode has not proved to be large and payable, but small scale paddocks do offer some cassiterite, and further drilling may yield better results.

At Dutsen Wai, cassiterite and columbite had been mined on a large scale from the alluvials, but reserves have diminished considerably and there is no more organised mining in the area.

Ririwai is the largest single lode so far discovered in Nigeria, and the development of a mine is in progress, where it is hoped that not only cassiterite but also sphalerite and galena will be produced. The Ririwai area had been exploited by the local people in the early part of the 19th century (Raeburn; 1924) and the mined tin was smelted and sold in the local markets as well as in other parts of the country.

The three areas have contributed at least 30 percent of the tin produced in the past. Although no figures are available on the production from individual areas values for the whole province can give a guide to the production history.

The production of cassiterite in Nigeria from 1904 to 1933 ranged from 1.5 long tons in 1904 to 4, 956 long tons in 1932 with an average of 6652 long tons per year. Between 1933

1.	Rock types present in the Complex containing the mineralised area.	a. Volcanic Cycle	Early Quartz
		b. Granitic Cycle	Arfved granit
2.	Rock types in the vicinity of mineralisation.		Biotit
3.	Host rocks containing the mineralisation.		Biotit
4.	Nature of the mineralisation.	a. Early dispersed in the bio	
		b. Late stage with greisen e	
5.	Economic form of mineralisation.		lodes,
6.	Size of mineralisation or lodes.		Large, mining
7.	Wall rock alteration.		Only i lodes
8.	Zoning.		Ore mi Zoning granit
9.	Types of veins.		fissur
10.	Ore minerals present.	a. In riebeckitic granite:-	
		b. In biotite granite:- colu molybdenite.	
11.	Potential of the lode.		potent and sp

R I R I W A I
rhyolites tuffs and agglomerates. Late intrusive rhyolites and intrusion breccias. roxene-fayalite-porphyries.
nite-fayalite-granite-porphyry-ring dyke. Biotite-granites. Riebeckite-aegirine- . Albite-riebeckitic-arfvedsonite-granites and minor acid dyke rocks.
and albite-riebeckitic-arfvedsonite granites
and albite-riebeckitic-arfvedsonite granites
te and riebeckitic granites. veins, only in the biotite granite.
eins, greisens, alluvial and eluvial.
he main lode is about 4.5 km long and 1 m. wide and over 450 m. deep. Extensive alluvial
the biotite granite, with greisens in contact with central veins carrying ores. wall rock (haematisation) in contact with greisens.
rals are telescoping. altered wall rocks. Central veins bordered by greisens, in turn bordered by reddened also bordered by normal granite.
filling with quartz and ore minerals.
rocklore, cryolite, amblygonite astrophyllite, thomsonelde ite, thorite, wolfram, cassiterite, galena, ophalerite, chalcopyrite, pyrite, monazite,
lly a viable mine and in the past columbite and cassiterite have been abundant while galena lerite will also be mined soon.

	DUTSEN WAI
a. Volcanic Cycle	agglomerates, quartz porphyry dyke and a late dolerite dyke.
b. Granitic Cycle	Crushed breccia riebeckitic-arfvedsonite-granite and biotite granite
	Biotite and albite-riebeckitic-arfvedsonite granites.
	Biotite and albite-riebeckitic arfvedsonite granites.
	Early dispersed mineralisation
	alluvial
	no lodes, small alluvial mining
	none, only granite weathering and decomposition
	none
	none
	none
a.	In albite-riebeckitic granite:- pyrochlore, cryolite, amblygonite and astrophyllite
b.	In biotite granite:- columbite and cassiterite.
	no lodes. little alluvial columbite and cassiterite.

Table 5.1. A COMPARISON OF THE THREE AREAS OF STUDY.

		GINDI	AKWATI
a.	Volcanic Cycle	Basic dykes, rhyolites and explosion breccias, quartz and feldsper porohyries.	
b.	Granitic Cycle	Granite porohyries, biotite granites, riebeckitic-arfvedsonite grenites and late basic dykes.	
			Basement Older Granite, granite porphyry, late basic dykes and mylonitised rocks.
			Older granite and mylonitised shear zones.
			Late stage in greisens, veins and disseminations
			greisen veins, alluvial and eluvial
			Extensive alluvial cassiterite in the Rop complex but very small greisen zones in the Gindi Akwati lode.
			Only greisenisation. No reddened zones as at Ririwai.
			no ore zoning
			fissure fillings in Older Granite, mylonite and greisens with quartz, feldspars and ore minerals.
			columbite, wolfram, sphalerite, chalcopyrite, pyrite mainly in dolerite dykes, cassiterite, ?bornite and little galena.
			Alluvial mining extensive and payable. Lode just under investigation but little prospect for high grade ores.

and 1950, both cassiterite and the associated columbite were mined with an average production of 13237 long tons of cassiterite and 771 long tons of columbite per year. Such production continued to rise and the production and export values of tin and columbite from 1950 to 1968 are given in Table 5.2 (Lukman; 1969).

Table 5.2. Production and Export values of Nigerian Cassiterite and Columbite.

Year	tons of cassiterite	tons of columbite	tons of Export cassiterite	tons of Export columbite
1950-51	11,333	899	11,167	856
1951-52	11,596	1,115	11,164	1,075
1952-53	11,758	1,406	11,942	1,367
1953-54	10,910	2,100	10,810	1,900
1954-55	11,026	3,152	11,107	2,996
1955-56	11,681	2,989	11,522	2,798
1956-57	12,722	2,397	13,584	2,259
1957-58	12,242	1,709	12,401	1,018
1958-59	7,414	846	6,738	1,103
1959-60	8,310	1,701	8,614	2,107
1960-61	10,596	2,201	10,864	2,976
1961-62	10,634	2,416	9,822	1,899
1962-63	11,275	1,941	7,896	2,195
1963-64	11,845	2,448	10,205	1,848
1964-65	12,154	2,579	9,335	3,222
1965-66	12,818	2,157	9,285	2,507
1966-67	12,660	2,185	9,254	2,338
1967-68	12,714	1,682	10,466	2,037
Total	203,688	35,923	186,200	36,492

CHAPTER 6.

Conclusions

This study has shown that the two granites at Dutsen Wai; the biotite granite and the albite-riebeckitic-arfvedsonite granite formed by differentiation from the same source. It has also shown that the Nigerian Younger Granite province contains two processes of mineralisation, one phase affecting both the riebeckitic-arfvedsonite granites and the biotite granites, and another phase affecting only the biotite granites and surrounding country rocks.

Riebeckitic-arfvedsonite Granites

At the time of crystallisation of these peralkaline rocks, residual fluids became increasingly enriched in volatiles as temperature dropped and crystallisation continued. The fluids continued to change continuously from an agpaitic magma to a sodium-silicate rich hydrothermal solution without super-critical phenomena. Thus the magmatic fluids progressed to hydrothermal fluids without an aqueous phase separating off. At late stages, and possibly near surface conditions, the confining pressure decreased to below the hydrostatic pressure, causing an immiscible liquid consisting predominantly of salts and volatile components to separate (Kogarko *et al*; 1974). This process led to the riebeckitisation of arfvedsonite and introduction of albite, microcline and quartz. It also accounts for the single period of mineralisation of these granites characterised by pyrochlore, fergusonite, fluorite, thomsenolite and cryolite. At the same time, the rocks were enriched in trace elements such as Be, Li, Cs, Cd, Sn, Zn, Rb, Sr and Mo. Owing to the high capability of alkaline melts to dissolve and retain volatiles (Kogarko; 1974), and the high content of volatiles and other metals in the component minerals (see Table

4.7), the concentrations of both the volatiles and metal ions in the co-existing gas phase was low. Also there was no separation of a silicate liquid or a water-rich supercritical phase since aplite dykes are absent and only little marginal pegmatitic effects are observed. Thus there is a marked absence of ores, veins and greisens in the peralkaline riebeckite-arfvedsonite granites.

Biotite Granites

Two phases of mineralisation occurred in the biotite granites. Chemical analyses have shown that the biotite granites are peraluminous (agpaitic ratio <1), which implies that the retention of a miscible aqueous phase is highly unlikely. As fractional crystallisation continued, the concentration of volatiles increased in the residuum until saturation when an aqueous phase separated. The cooler crystaline portions of the granites in the roof zones of the intrusions were invaded by the then immiscible phases from the still crystallising granites at slightly deeper levels. The invading fluids introduced alkali feldspar and quartz, transformed biotite into siderophyllite and protolithionite, and produced the greisen-fissure veins. However this process occurred in stages, resulting in two phases of mineralisation:-

a. The pre-joint autometamorphic mineralisation

This process occurred during the consolidation of the biotite granites. At this stage K-feldspars replaced earlier perthites, while albite developed. Silicification and recrystallisation changed the original rock texture. This stage also introduced dispersed mineralisation with thorite, columbite, xenotime and hafnium-uranium rich zircon. Other trace elements enriched at this stage include Rb, Li, Y, Zn, Sn and Pb. As the biotite granites (now apogranites) finally consolidated,

contraction caused distinctive joints, fissures and fractures which were then utilised by the late hydrothermal fluids for the formation of the second phase of mineralisation.

b. The post-joint replacement greisen-mineralisation

This phase of mineralisation took place in the roof zones of the cooling consolidated biotite granites. It involved a metasomatic introduction of cassiterite, together with abundant sulphide minerals into crystalline host rocks along cooling joints, fissures and fractures. The mineralisation produced progressive replacement of original host rock minerals, and affected the country rocks as well. The replacement processes occurred in a definite sequence with small variations in the products, depending on the rocks in which they occurred.

However not all the two processes are found in all the biotite granites. Some biotite granites may be affected by the pre-joint (albitisation) phase of mineralisation without the post-joint phase while some biotite granites contain both phases and some contain only the post-joint phase of mineralisation.

Each area studied may contain certain features which are absent in other areas. The findings at each area are summarised here:-

I, Ririwai

Both the pre-joint and post-joint mineralisation occurred in the Ririwai biotite granite. The pre-joint mineralisation caused extensive albitisation particularly at depths of about 400 m below the present surface level where there is thorough recrystallisation and disseminated ores are abundant. Columbite, sphalerite and some cassiterite was disseminated in the granite at this time.

The post-joint mineralisation was on a larger scale, producing a large vein lode, many smaller veins, greisens and

abundant ore minerals such as galena, sphalerite, cassiterite, chalcopyrite and arsenopyrite. The veins consisted of quartz, Li-Fe and Li-Al micas, chlorite, topaz and/or fluorite with ore minerals, and these were enriched in the wall rocks as well. The sequence of replacement has been established as follows:-

(1) Haematisation and Kaolinisation

These took place at the same time. The kaolinisation involved the partial alteration or replacement of feldspars, forming K-feldspars and clay minerals, most prominently kaolinite. Haematisation involved the staining of the K-feldspar with haematite formed from iron not taken in by new minerals formed from pre-joint mineralisation as well as from the kaolinisation. The haematisation resulted in the zone of wall rock reddening adjacent to veins and greisens.

(2) Chloritisation and Sericitisation

These processes too took place simultaneously although chloritisation appeared to have started before sericitisation. The original biotite of the host rock was partially chloritised and in some places wholly replaced by chlorite, while at the same time sericite developed from feldspars. Small amounts of sericite also formed from alteration of the developed chlorite.

Ore Concentration and Fluorite

The chloritisation and sericitisation were accompanied by the heaviest concentration of ore minerals; sphalerite, chalcopyrite, pyrite, arsenopyrite and abundant fluorite. At this stage, small veins containing the above ores as well as cassiterite grains in the mica surrounding the veins started to develop.

(3) Greisenisation

The greisenisation phase was characterised by the formation of new micas identified as mainly protolithionite and siderophyllite in association with quartz. At this stage,

both cassiterite and topaz were introduced while some of the earlier formed fluorite decreased and nearly all of the haematite staining destroyed. It is the writer's belief that the earlier fluorite decreased because some of the fluorine went into the formation of topaz while the released lime went into the formation of a clay mineral observed in the small vugs in the greisens associated with a feldspar believed to be adularia. The haematisation was destroyed, and the iron content went into the formation of the greisen micas.

(4) Silicification

The last process was silicification with quartz veins infilling fissures. The smaller quartz veins crossent all the previous products of alteration. This process involved an increase in the proportion of quartz to other minerals in the altered wallrock as well as introduction of massive quartz in the fissure fillings. This process also deposited more sphalerite, cassiterite and galena, and was the only period of wolfram mineralisation, being restricted to the quartz veins.

II Gindi Akwati

At Gindi Akwati, only post-joint mineralisation occurred, with Older Granite as the host rock.

1, Shearing and mylonitisation

The Older Granite was sheared and fractured by the emplacement of the Granite porphyry.

2, Argillisation and Haematisation

The argillisation of the Older Granite started along the shear planes with the replacement and partial conversion of the strained and granulated feldspars into clay minerals, most prominently montmorillonite. At this time little haematite also developed and gave the rocks a brownish outlook.

It will be observed that in the biotite granite the clay mineral kaolinite was mostly formed at this stage, while in the Older Granite montmorillonite appears to be the most prominent clay mineral. It is the writer's opinion that at Gindi Akwati, alteration took place under more alkaline conditions than at Ririwai. At Gindi Akwati, the Older Granite has a granodioritic composition with low K and relatively more Mg and Ca than in the biotite granite hence the conditions were more favourable for the formation of montmorillonite. At Ririwai the biotite granite contains more alkali feldspars and has an acidic composition which would favour the formation of kaolinite.

3, Chloritisation and muscovitisation

The biotite of the Older Granite was partly replaced or converted to chlorite and muscovite. Very little sericite was formed. At this stage abundant sphalerite and fluorite were introduced. Other minerals introduced at this stage included chalcopyrite, pyrite, cassiterite, bornite, molybdenite and greenockite. Besides the ore minerals and a few grains of quartz and feldspars of the original rock, the rest of the rock contained mainly biotite, chlorite, muscovite and small mica-quartz-fluorite veinlets started to develop.

4, Greisenisation

The greisenisation process was characterised by complete elimination of original quartz and feldspars, formation of small amounts of Li-Fe and Li-Al micas, introduction of abundant topaz in some sections with a decrease in fluorite. More sphalerite was also introduced. However the resultant greisens still contained biotite, muscovite and high proportions of chlorite.

5. Silification and feldspathisation

The last process was quartz-feldspar infilling fissures crosscutting all the previously formed features of the alteration processes. The amount of quartz infilling fissures was subordinate to the feldspars and in some veins albite crystals developed at centres of the veins. Both wolfram sphalerite and a little fluorite and cassiterite were introduced at this stage.

III Dutsen Wai

Here, the early dispersed phase of mineralisation introduced albite, microcline and recrystallisation in the albite-riebeckitic-arfvedsonite granite accompanied by enrichment in trace elements and the minerals pyrochlore, astrophyllite and amblygonite.

In the biotite granite there was a small scale pre-joint dispersed mineralisation mainly of columbite and cassiterite. No veins and greisens developed and concentration of columbite and cassiterite is present only in the alluvials. Thus the alluvial concentration must have formed by:-

1, Weathering

The weathering of the biotite granite concentrated the dispersed mineralisation in the alluvials. It is also the writer's opinion that the roof zones of this granite may have been affected by post-joint mineralisation but weathering of the roof zones may have concentrated cassiterite in the alluvials (Chapter 4).

2, Decomposition

The weathered minerals decomposed and released their tin content as well as the columbite into the alluvials. Perhaps here columbite may not be included but such a process might be possible if minerals decomposing contained Ta and Nb.

3, Oxidation

The tin leached from the decomposed minerals underwent hydrolysis by groundwater action and was subsequently oxidised to cassiterite. Such a process is feasible as discussed in Chapter 4, but such a formation of cassiterite may be too fine grained for recovery. However it is possible that tin released from other minerals could form overgrowths on originally accessory cassiterite from the weathered rock.

This study has also revealed that the product of wall-rock alteration and associated iron-ore minerals depend on the host rock in which the mineralisation occurred. If it occurred in biotite granites, the resultant greisens would be highly enriched in silica and quartz with little fluorite and topaz. If it occurred in Older Granite with an initial plagioclase composition (as at Gindi Akwati) a mica greisen would result and high depletion in silica and quartz, locally enriched in fluorite and topaz. In such a case abundant fluorite developed due to the available lime released by the destruction of the feldspar of the Older Granite, while topaz would form at the greisenisation stage due to the available fluorine from partly destroyed fluorite, which had developed at the chloritisation-sericitisation stage as well as the alumina released by the complete destruction of the original feldspar at the greisenisation stage. The lime released by the partial destruction of fluorite would have contributed to the final plagioclase formation at the feldspathisation stage.

The stages of alteration processes in the two cases can be summarised thus:-

Biotite Granite		Older Granite
		Shearing and mylonitisation
Kaolinisation and Haematisation		Argillisation and Haematisation
Chloritisation	major ore	Chloritisation and Muscovitisation
Sericitisation	introduction	Sericitisation
Greisenisation		Greisenisation
Silicification		Silicification and felspathisation
		Feldspathisation.

This scheme is based on the writer's findings at the areas concerned and may be different in other areas. Furthermore, Kinnaired (Private discussion) suggested a scheme (much the same as the writers') for alteration in biotite granites and her scheme is presented below.

1, Argillisation and Haematite formation

2, Chloritisation

3, Sericitisation

4, Greisenisation

5, Silicification (rarely with feldspar growth).

Sphalerite and Cassiterite

This study has shown that by far the most abundant ore mineral at Ririwai and Gindi Akwati is sphalerite. In most of the greisen zones, cassiterite is subordinate to sphalerite and may even be absent. At Gindi Akwati, the late dolerite dykes are highly enriched in Zn compared to the normal Zn values in basic rocks, although they contain no visible sphalerite. In general sulphide ores may all become more abundant than cassiterite.

Pyrite

The dolerite dykes at Gindi Akwati are highly mineralised with pyrite as a primary component of the rocks, and bears no

direct relationship with the post-joint mineralisation in the Older Granite.

Zoning

There is no definite zoning of ore minerals. However individual veins may exhibit local zonation of ores with sphalerite at centres of veins and cassiterite on the margins within a micaceous matrix. The general occurrence of ores is that of telescoping, affecting the host rocks at random, which is an indication of a near surface deposition and mineralisation by several phases of hydrothermal fluid action.

Mineral Associations

At Ririwair, the mineralisation has the quartz-mica-topaz-fluorite-cassiterite-sulphide association, while at Gindi Akwati there are two associations; the quartz-mica-topaz fluorite-cassiterite-sulphide and the feldspar-mica-fluorite-topaz-cassiterite-sulphide types.

It is not clear what role the mineralising fluids played in the different processes of alteration and ore deposition since the actual chemical composition of the ore fluids, the chemical causes and changes involved during mineralisation, the degree of water saturation and the exact pressures and temperatures of formation are unknown. However the results of this study are compatible with field occurrences and their use combined with further research will surely reveal more about the Nigerian Younger Granite Province and its associated mineralisation.

Discussion and Suggestions.

Petrographic and chemical analyses have shown that although the peralkaline and the biotite granites have a similar magmatic source, the late hydrothermal fluids that affected the rocks may be of different sources. This differ-

ence is observed mainly in the intensity of recrystallisation and the new growth of albite and microcline which are more abundant in the peralkaline granite.

1, During the dispersed phase of mineralisation, different elements concentrated in the two rock types, for instance the minerals pyrochlore, cryolite and amblygonite are confined to the agpaitic riebeckitic granite while columbite is restricted to the plumasitic apogranite. The differences must be related to the composition of the hydrothermal fluids that introduced these minerals.

2, The post-joint mineralisation in the biotite granite involved late hydrothermal fluids as well as the host rock in which mineralisation occurred. Although the chemical composition of the host rocks is known, the chemical composition of the fluids is not known. The alteration processes are discussed based on the compositions of the altered wall rocks, and the actual chemical transformations are not completely known.

Further work has to be done by studying the D^2/H, O^{18}/O^{16} isotopic ratios in some of the minerals which would indicate a possible source of water in the fluids and hence the origins of the mineralising fluids associated with both rock types. This will also clarify the mineralisation in the Older Granites and basement rocks where biotite granites with which mineralising fluids are supposed to be associated are not visible, for instance at Gindi Akwati.

Perhaps Pb isotope studies on some minerals like monazite and galena will give ages that correspond with the ages of the host rocks. This will also aid in understanding

the source of the hydrothermal fluids associated with the minerals as well as their host rocks. Further work should include fluid inclusion studies in the vein minerals, which will indicate not only the composition of the mineralising fluids, but also the temperature at which the ores were formed and the form in which they were transported.

3, It has been found in this study that sphalerite is more abundant than cassiterite in two of the three areas studied. Furthermore the dolerite dykes at Gindi Akwati have been highly enriched in zinc and also contain pyrite believed to have crystallised with the rocks. In the past all attention on mineralisation in this province has been centred on cassiterite. It is necessary to study more areas of mineralisation with particular attention on the extent of Zn mineralisation. At Gindi Akwati, more work should be done on the dolerite dykes, both in the mineralised zone and outside the zone to compare the Zn values as well as the pyrite mineralisation. This will tell whether the dolerite magma had interacted with the mineralising fluids only in this zone or even outside the zone. Such a study combined with the studies on sphalerite in other areas will reveal whether the dolerite magma was initially rich in Zn and iron sulphides as well as to establish whether this area is not just a tin province but also a Zn province.

4, At Dutsen Wai, I have put forward two theories for the origin of the alluvial cassiterite. The most likely one is that the roof zones of the biotite granite were affected by post-joint mineralisation with veinlets containing cassiterite. Subsequent erosion and weathering of the roof zones was responsible for the accumulation of cassiterite in the alluvials. The cause of the barren granite as it is now would be the depth of erosion. The second theory of leaching tin from minerals of

the decomposed granite, particularly biotites also cannot just be discarded. Further work is therefore needed not only on the measurement of the tin conent of biotites in this province, but also on the mechanism of release of tin from biotites and how important this mechanism is in the concentration of tin which is abundant in the alluvials in this province.

5, At Gindi Akwati, mineralisation is qssociated with feldspathic veins while at Ririwai feldspathic veins are lacking. However at deeper levels of the present Ririwai surface, feldspathisation has been observed in the biotite granite associated with the mineralisation, while silica has been leached from this zone. Perhaps the causes may be related to depth of erosion or pressure and chemical conditions associated with the mineralising fluids. At Ririwai the hydrothermal fluids may have leached silica at depth and later released it at lower temperatures and pressures at the surface into the greisens and in the veins as quartz. At Gindi Akwati the reverse could have happened with varying chemical composition of the mineralising fluids. Perhaps there may be silicification at depth with leaching of feldspars which were later deposited in the veins at surface. If the temperatures of formation and the chemical compositions of the mineralising fluids are known such phenomena could be explained better.

6, It has been observed that wolfram occurs restricted in the greisen veins or in mineralised quartz veins which penetrate basement rocks adjacent to the Younger Granites. If the temperature, chemical composition, origin and chemical reactions taking place during ore deposition are known, an explanation can emerge which better explains such occurrences.

7, At Gindi Akwati, the lode does not contain economic

mineralisation for commercial exploitation as can be seen from the present available data. However there is a small increase in ore concentration with depth. It is the writers' opinion that there may be a biotite granite batholith with more mineralisation at depth. It will be a good idea to drill further as well as putting more drill holes to intersect the largest greisen zone at depth. This might give a better idea of the nature of the mineralisation and ore concentration.

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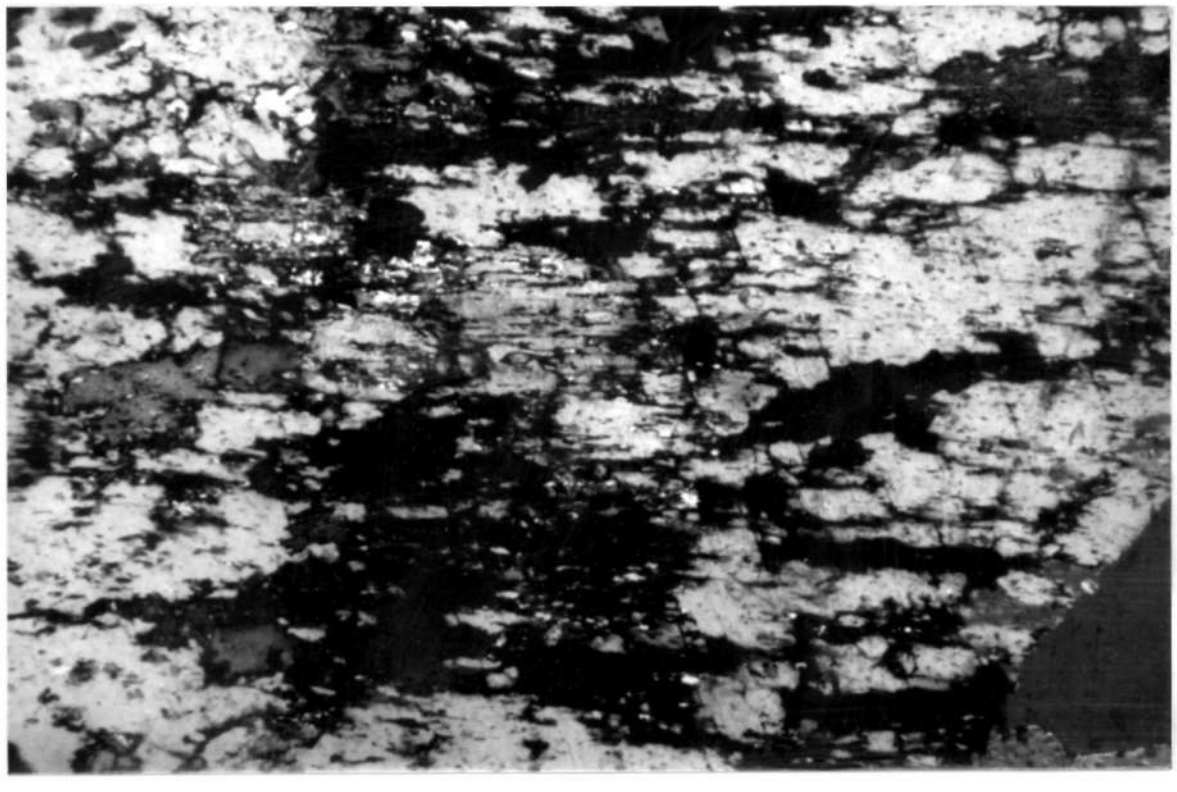


Plate 2. Sheared Older Granite with fluorite (dark) developed along cracks; Ordinary illumination., x35



Plate 3. Greisenised Older Granite. Large dark patch is a matrix of sphalerite and fluorite; Cross, x35

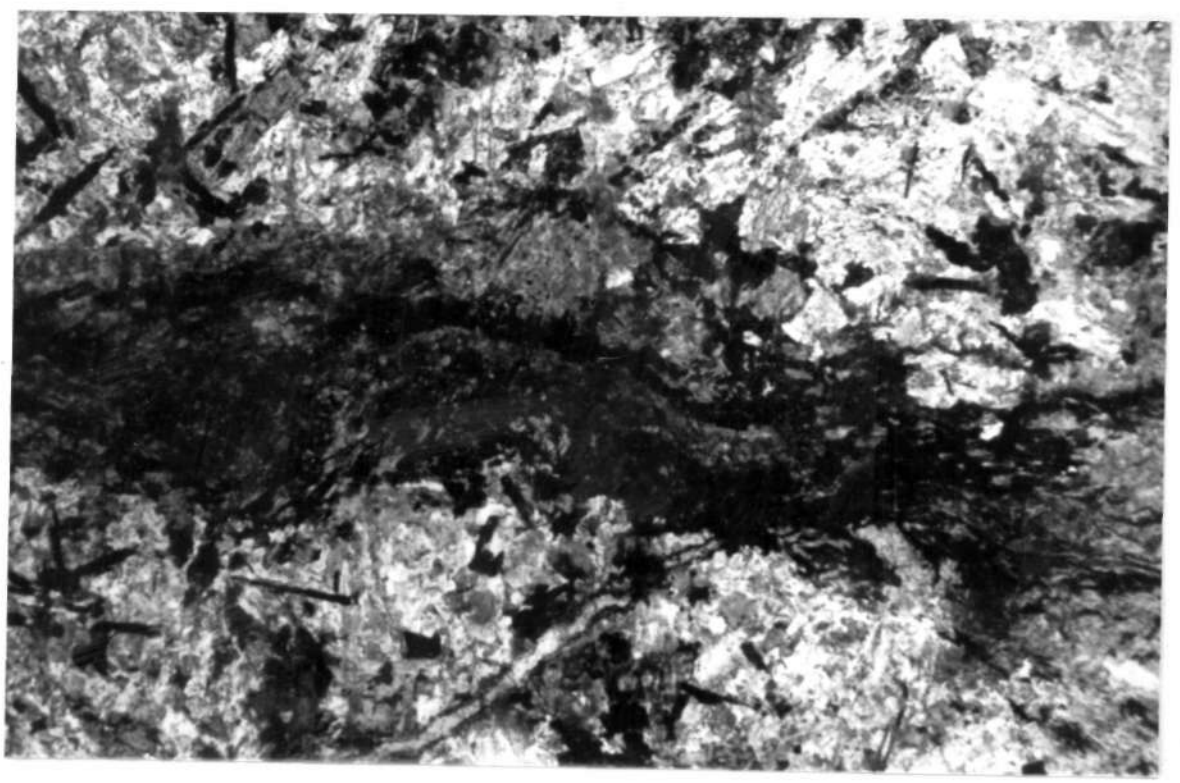


Plate 4. Calcite vein in a dolerite dyke;
Ordinary light, x35

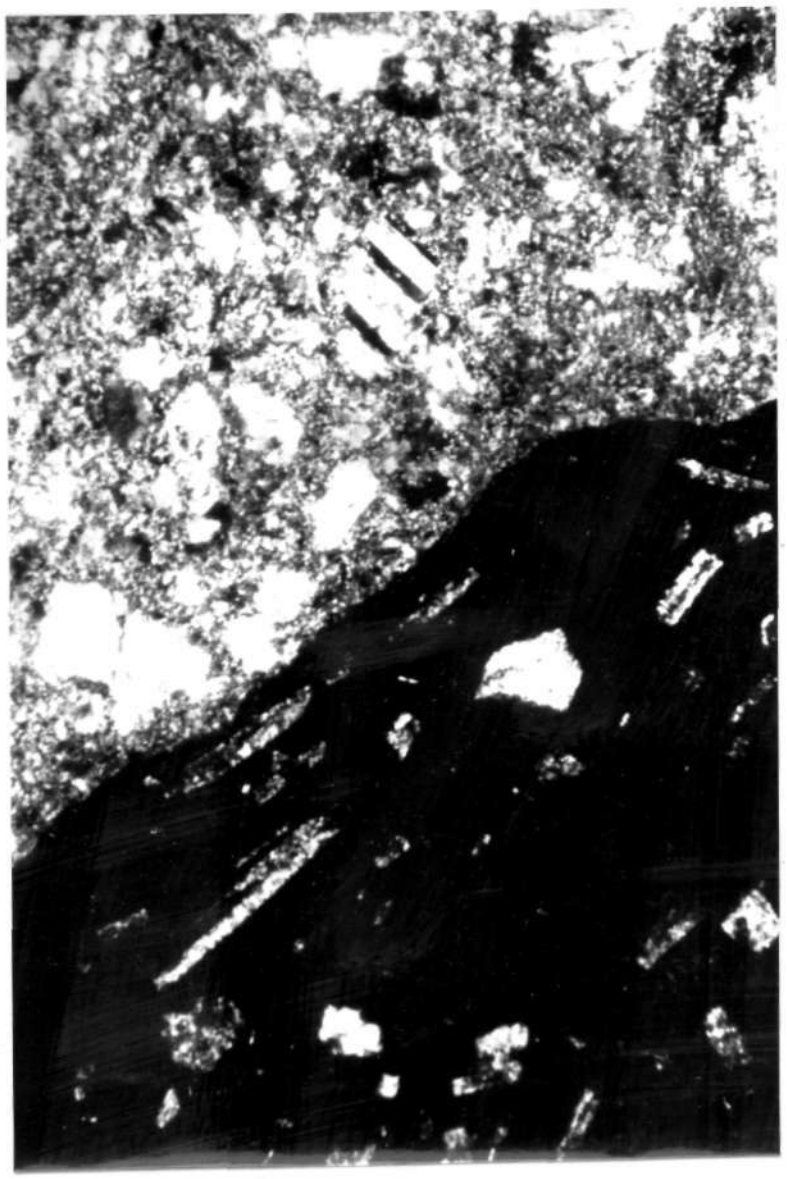


Plate 5. Contact of dolerite dyke (dark) and greisenised granite (grey); Crossed, x35



Plate 6. Albite-riebeckitic-arfvedsonite granite. Dark areas are overgrowths of riebeckitic-arfvedsonite (darkest zone) and aegirine (dark brown); bottom right dark crystal; cross X35

APPENDIX II.

Explanation of some of the terms used.

1, Agpaitic ratio = the molecular proportions of potash (K_2O) and Soda (Na_2O) divided by the molecular proportion of alumina (Al_2O_3), expressed

$$\frac{MP\ (K_2O) + MP\ (Na_2O)}{MP\ (Al_2O_3)}$$

2, Agpaitic rock is one which has agpaitic ratio greater than 1 and plumasitic rock is one with the ratio less than 1.

3, Basement refers to the country rocks composed mainly of Older granites, gneisses and migmatites.

4, Greisen applies to an altered rock due to hydrothermal fluid action with introduction of micas, quartz and/or feldspars and ore minerals.

5, Greisenised granite refers to an altered rock as above but with some of the minerals and textures of the original rock still preserved.

6, Lode refers to a zone in which ore minerals have been introduced usually in the form of veins, fracture zones accompanied by alteration of the host rock.

7, M.P. = molecular proportion.

8, P.P.M. = parts per million.

9, Primary mineralisation here means ore minerals formed at the time of crystallisation of the host rock or introduced at later stages by hydrothermal fluid action.

10, The name Ririwai has been referred to in previous literature as Liruei but the actual place is known as and called Ririwai.

11, Sample Numbers: DW refers to Dutsen Wai. The following number system has been used for Gindi Akwati e.g. E_1 4.5 means sample from E core, tray No. 1 at a depth of 4.5 m. At Ririwai L13 is the core number and the numbers after L13 refer to depths at which the sample is taken.

12. Secondary mineralisation refers to ore minerals found as eluvial or alluvial after a rock with primary mineralisation is weathered.

A P P E N D I X IIA

The following references:-

(1) Black (1971)

(2) Turner (1971)

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